PULSE LASER INSTRUMENTATION

by

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AIR FORCE WEAPONS LABORATORY
Research and Technology Division
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This research on pulse laser diagnostics covers the period from April 1962 to December 1963. Preliminary data were collated and a draft report was prepared in September 1964. However, because of reevaluation of data contingent on the state of the art, final publication has been deferred until June 1965. This document is intended for technical personnel who have some familiarity with current laser technology. The research and the resulting device development was supported by the Advanced Research Projects Agency under ARPA Order 313 as part of the Air Force Systems Command Project 8814, Program Element No. 6.25.03.01.5.

The authors wish to express gratitude to the following: Mr. David Polley for his suggestions, calculations, and experimental support; Dr. John Reishus and Dr. Petras Avizonis for helpful discussions; Airman Arthur Goodman for photographic support; and Mr. Ken Walters and Airman Antonio Regal for executing the finished drawings.

This report has been reviewed and is approved.

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ABSTRACT

The development of the techniques and devices used to measure pulse laser output at the Air Force Weapons Laboratory is described. Included are discussions of principles, physical design, associated circuitry, and impedance-matching techniques. The instrumentation system consists of a total beam calorimeter suited to the laser energy range and an integrator whose signal is correlated to the calorimeter measurement. The calorimeter is either an absorbing surface or volume arranged so that the energy is well trapped. The surface absorber is a thermally isolated hollow silver sphere whose inner surface has been highly polished and whose heat capacity can be accurately calculated. The laser beam is admitted into the sphere at the focal point of a short-focal-length lens through a very small hole off center of the sphere. The volume absorber is cone-shaped as a result of various requirements and considerations. Thermistors or thermocouples are used to measure the resultant temperature rise. The use of these devices has several merits, chiefly high accuracy, stability, and relative simplicity. In addition, the devices lend themselves to the measurement of a wide range of energy densities; e.g., by variation of the diameter of the sphere in the first mentioned device. An entirely impedance-matched circuit was designed for the high-speed light-sampling diode. Several integration techniques were considered and three were selected; the one utilized depended on the experimental situation.

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ILLUSTRATIONS

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

SECTION I

INTRODUCTION--PRIMARY GOALS

The primary concern throughout the research reported here has been to obtain with the least complication accurate measurements of laser beam characteristics.

The difficulties involved in calibrating optical devices and the possible variation of supposed constants at high photon fluxes divert one from such difficult measurements as reflectance, quantum efficiency, and other complexities. If one wishes to measure the energy and power in a laser beam, it is necessary to know only the total energy (as the absolute quantity) and the time variation of the intensity merely on a relative scale, i.e., a "shape"--assuming the shape can be truly related to the intensity variation. The important fact here is that only one device must be absolute. This can then be used to calibrate a relative intensity integrating device. Further, the absolute device can be allowed some complication since it will be used only for calibration. The relative integrator permits a great deal more freedom in its design. The relation between total energy value and the relative value will naturally depend on the type of integrator employed. Generally the dependence is linear, since the integration of the intensity over time (sampled across the entire beam) is proportional to the total energy and most electrical integration techniques produce a signal nearly proportional to the mathematical integration. Figure 1 shows the relation. This general technique accumulates still further merit when certain relative devices are used.

The absolute device will be placed exactly where the experiment is to be performed to allow calibration under the exact conditions of the experiment. Clearly, the quality of the diagnostic system depends heavily on this absolute device.

Figure 2 is a schematic of a typical setup in which two relative detectors sample the beam with, for example, glass or fused-quartz plates.

In general the time-resolved detector is of the photoelectric type. The inherent response characteristics of this sensor are of great advantage in

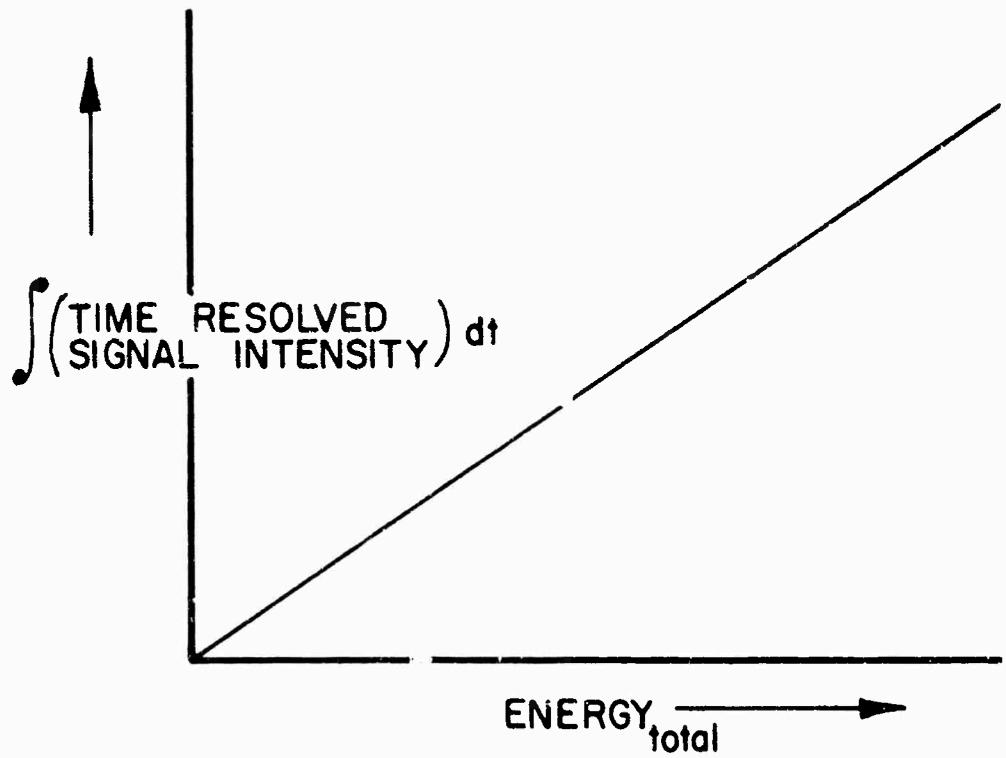

Figure 1. Absolute-to-Relative Device Relation

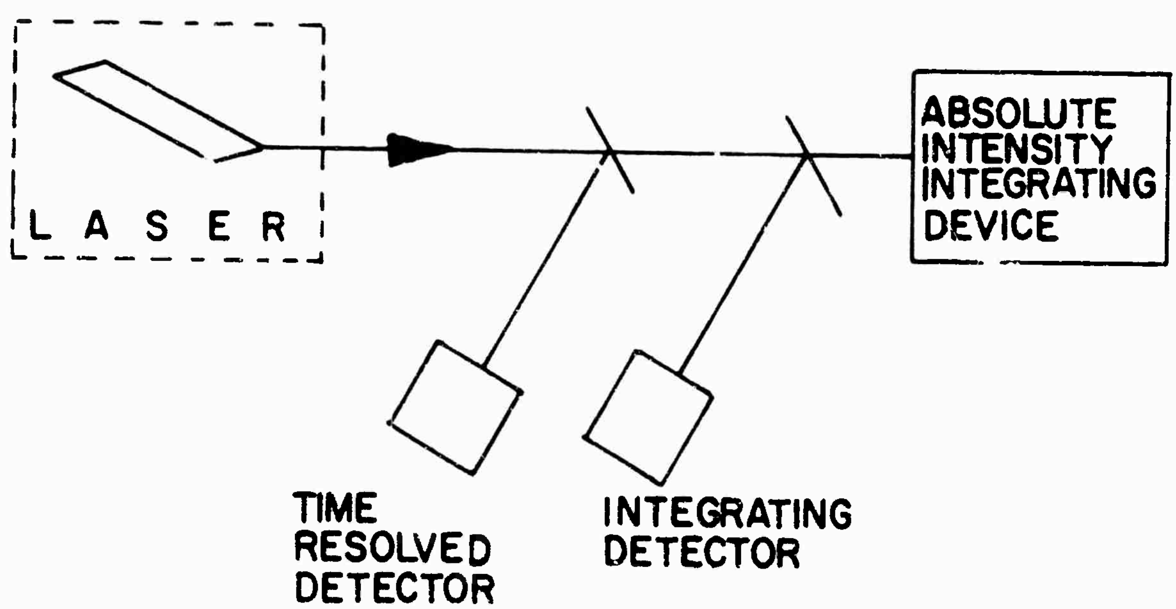

Figure 2. General System Configuration

fast pulse work. Integrating techniques involve use of either a photodetector with integration circuitry or a more direct integrating sensor. The absolute device is generally a blackbody-type radiation trap so designed that one is certain that the radiant energy is converted to heat rather than lost to assorted stable energy level changes in the absorber, etc.

SECTION II

THE ABSOLUTE MEASUREMENT

This section could easily be called calorimetry because the basic premise of the techniques used for this measurement is that nothing usable is more accurately known than the heat capacities of simple materials.

If one can capture the light beam and allow it to heat only the substance desired, then one can, at leisure, measure the energy inserted. This involves (1) making certain that the energy has actually been trapped (not merely part of the energy to which has been added reflection or absorption coefficients--these actually weaken the technique), (2) preventing energy losses from the absorber during measurements, and (3) ensuring that the temperature absorbing material comes to equilibrium. The second requirement, preventing energy losses, can be relaxed somewhat (later in text).

Energies from 10^{-3} to 10^{4} joules and greater can be conveniently and accurately measured with instruments described herein. The upper limit is determined by breakdown of optical components, which is a strong function of power.[1] Energy is not itself a limitation. In fact, with more and more energy, new measuring techniques are possible; i.e., for a given sensor signal, greater heat capacities can be used.

1. Heat Sensors

The recommended sensors are either thermistors or thermocouples. Other kinds of heat sensors involve greater heat capacity, greater difficulty in making good thermal contact, larger conductivity losses, etc., and so are not recommended for this type of measurement.

a. Thermocouple

The thermocouple has the principal advantages of linearity,[2] self-contained sources, voltage output, and the ease with which one can obtain zero voltage as the starting point. The principal disadvantage is a lack of

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[1] Experimentally determined at the Air Force Weapons Laboratory.

[2] Relatively small changes in temperature.

reproducibility in very low microvolt signals. If thermocouples are used, then it pays to use the best quality wire to prevent extraneous emfs.

Only the change in temperature is of interest, so the slope of the temperature-to-thermocouple output curve is sufficient. A typical value is 39.6 μV/C° (for Chromel-Alumel). Clearly, amplification is needed and one has to be careful regarding the allowable input impedances. At least one company manufactures an amplifier for thermocouples and other very low impedance sources.[3] Other amplifiers have been checked against controlled, known temperature changes ($\pm$0.01°C) with #40 thermocouple wire, and the proper values within amplifier accuracy.[4] These have a low frequency response (about 1 cps) but if thermal decay times are long as they should be, this is unimportant. One can finally readout a time history on a recorder or an oscilloscope.

The concern is with the total thermal conductance away from the absorbing body, so the thermocouple should be as small as possible. Number 40 wire seems a good compromise between too large and unworkably small. Junctions may be most easily made with a small spot welder, with a typical welding energy of 16 watt-seconds. The quality of the weld should be examined with a magnifying glass. At the same time, the second or reference junction should be welded. No more than one pair of junctions is required since this is an equilibrium measurement.

b. Thermistor

The thermistor requires more sophisticated circuitry than the thermocouple, but its reproducibility is generally much greater, thus allowing total changes in temperature of the order of hundredths of a degree. The temperature response curves of typical thermistors used in these applications are found in figure 3. Although the time response for these is listed by the manufacturer as about 1 second, careful experiments at AFWL show that, when the thermistor is attached to a heat sink, the response is much faster.

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[3] Applied Research Associates MA-51.

[4] E.g., Hewlett-Packard 425A

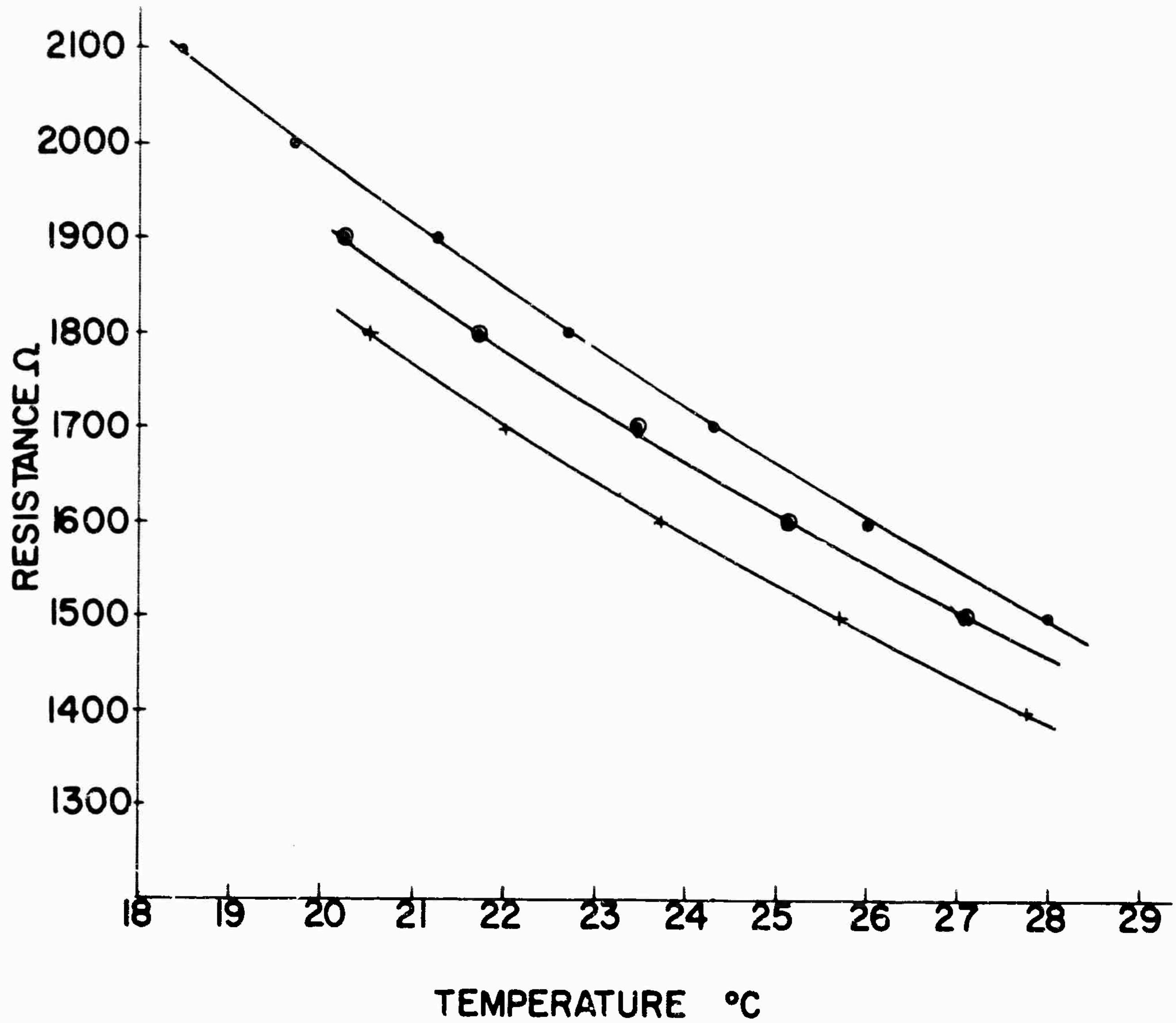


Figure 3. Temperature Calibration of Three 32 CH2 Gulton Industries Thermistors

Since even the same types of thermistors vary in individual temperature response, each must be calibrated. A suggested calibration scheme is shown in figures 4 and 5.

Only a temporary deflection will be read on the galvanometer. This and the resistor in series with the battery are designed to limit the dissipation of the thermistor--to protect it and to ensure that the thermistor is at thermometer temperature. Care must be taken to operate the thermistor in the proper voltage/current region. Figure 6 indicates typical values. The dissipation curves will probably not vary by as much as a factor of 10 for thermistors used in this application.

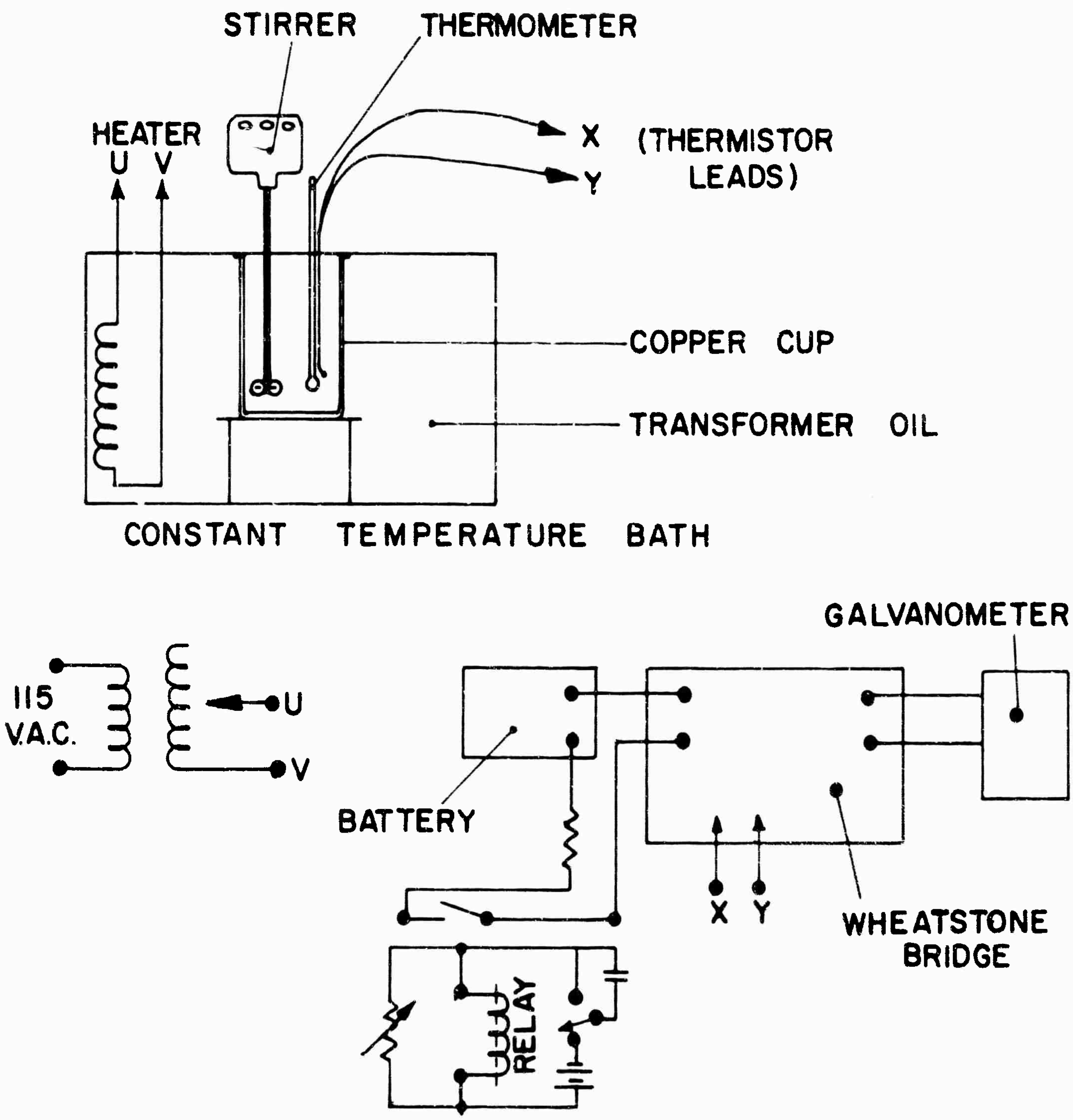
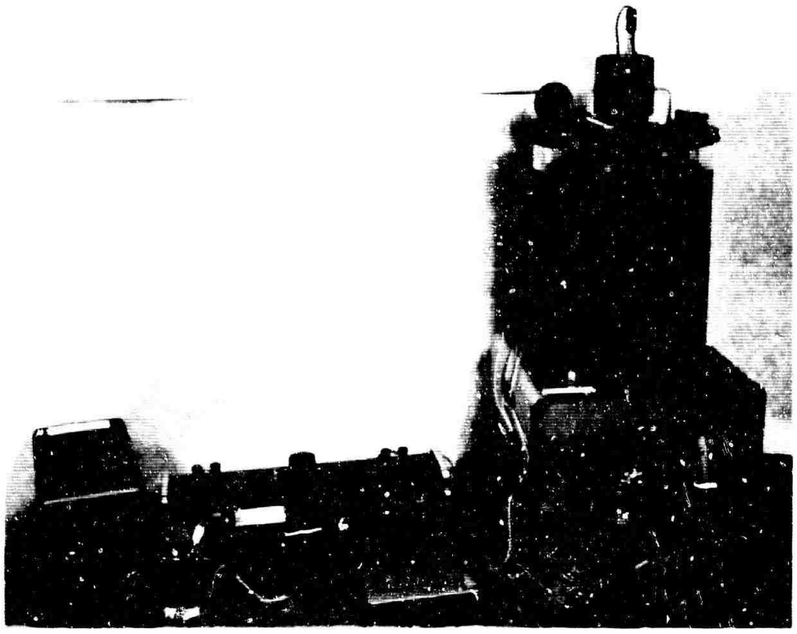


Figure 4. Schematic of Thermistor Calibration



a. Constant Temperature Bath

b. Calibration Setup

Figure 5. Thermistor Calibration Devices

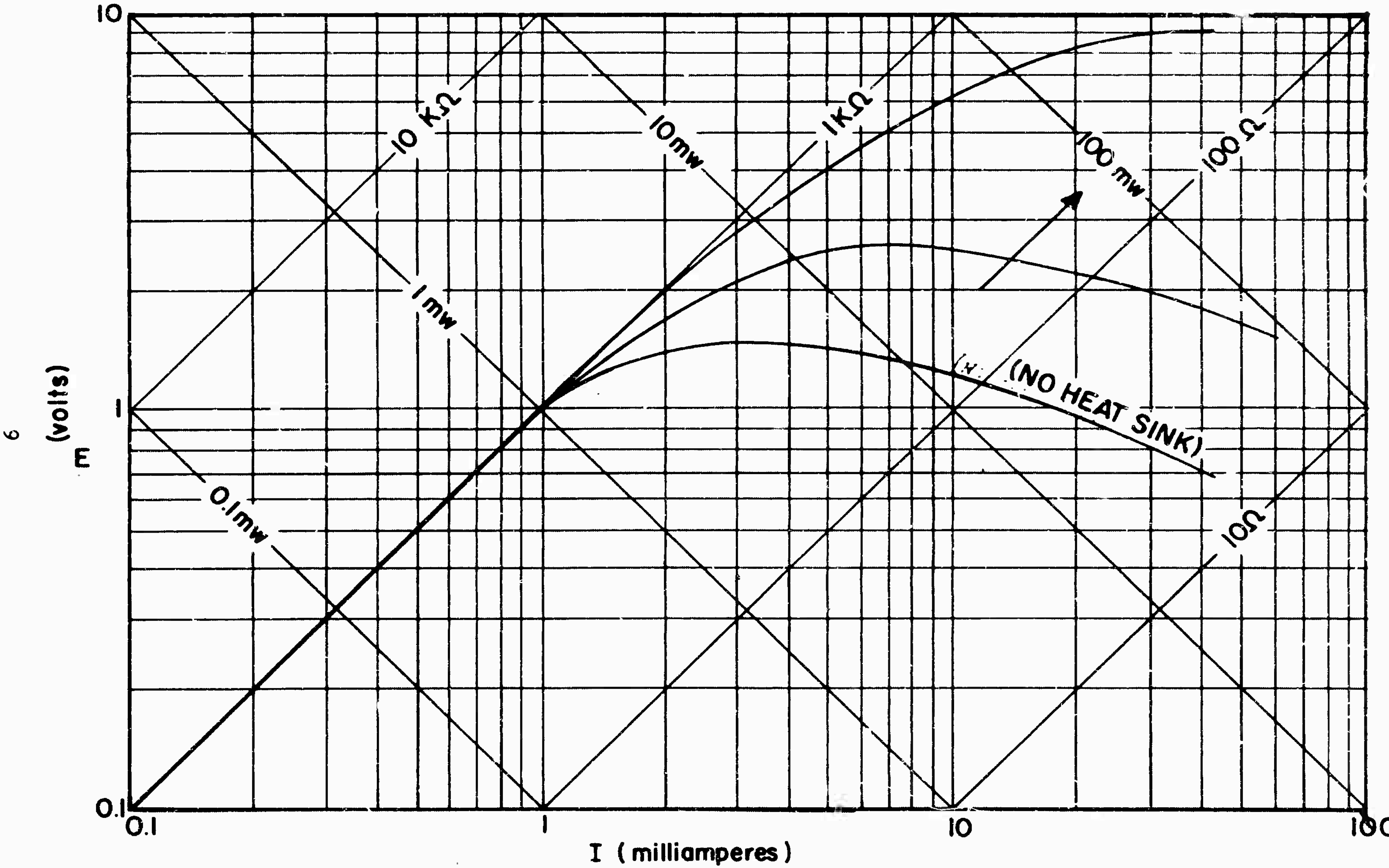


Figure 6. V-I Curve for Typical Thermistors with Heat Sinks
(Heat sink capacity increases as indicated by arrow)

Figure 7 is an enlargement of a Gulton Industries type 45DC5 bead thermistor with adjacent 0.020 in./div. scale. Thermistors come in a large assortment of base resistances and sizes.[5] As with thermocouples, the smaller the size, the better.

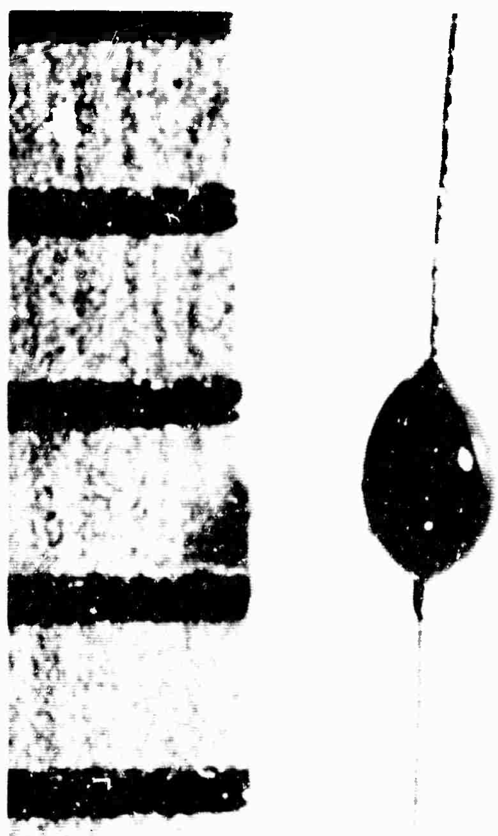


Figure 7. Thermistor (greatly enlarged)

Two circuit alternatives are shown in figure 8. In each case the primary purpose of the circuit is to provide a voltage the variation of which is related to the resistance change. If the bridge is balanced at the start, the bridge circuit gives a signal only when R_T changes, although the relationship of voltage output to change in R_T is not linear.

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[5] Suggested sources:
Gulton Industries, Metuchen, NJ
Fenwal Electronics, Framingham, Mass
Micro-Systems, Inc., San Gabriel, Calif

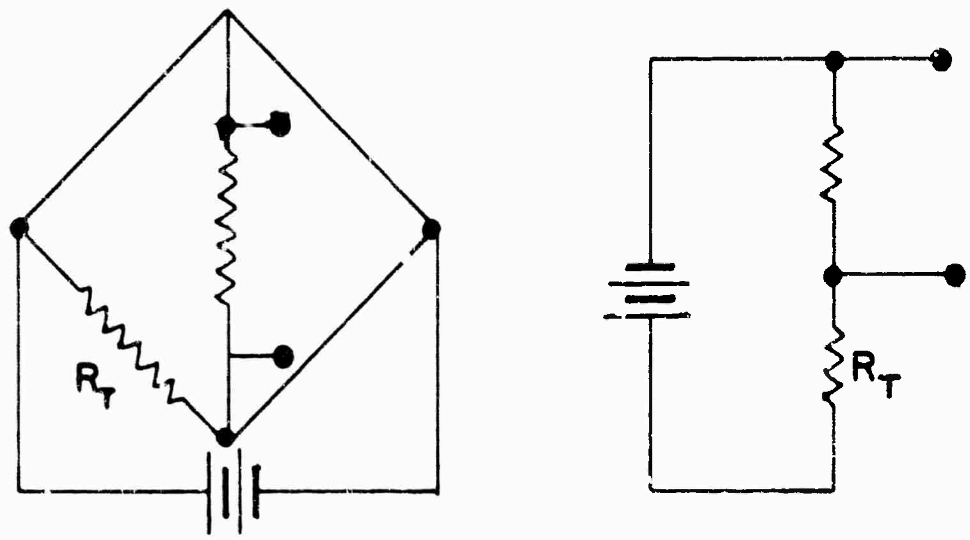

Figure 8. Simplest Thermistor Circuits

A better design puts a relatively large resistor in series with R_T in the same leg. Within expected changes, one can then choose the limits of linearity. This bridge can be followed by an amplifier and recorder.

One specific setup used a type Q (ac bridge) Tektronix preamplifier which includes all this circuitry and records the final information on a slow-writing oscilloscope trace.

The question now arises of how gain is checked in the system. This is most simply done by the addition of a known resistance to that of the thermistor. One may use several values initially to check linearity as well as gain. The system can be made very nearly linear, depending on the signal beat that can be tolerated. If a simple push-button switch is inserted in the proper place in the system, then the entire calibration can easily be done as a check before each experiment. The calibration change in resistance should be about the same as that expected in the experiment and should be done on the same trace for comparison. This calibration gives a normalizing value.

$$\Delta R = \frac{\text{thermistor signal}}{\text{calibration signal}} \times \text{calibration resistance change value}$$

Figure 9 shows a typical trace shape.

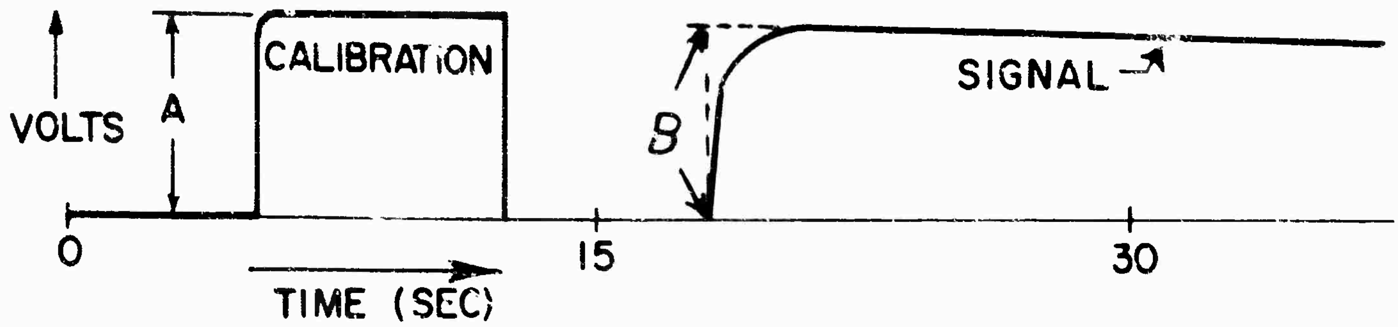

Figure 9. Calorimeter Trace Shape

$$\Delta R = \frac{B}{A} \times \text{calibration resistance change}$$

Figure 10 is a schematic of the thermistor circuitry.

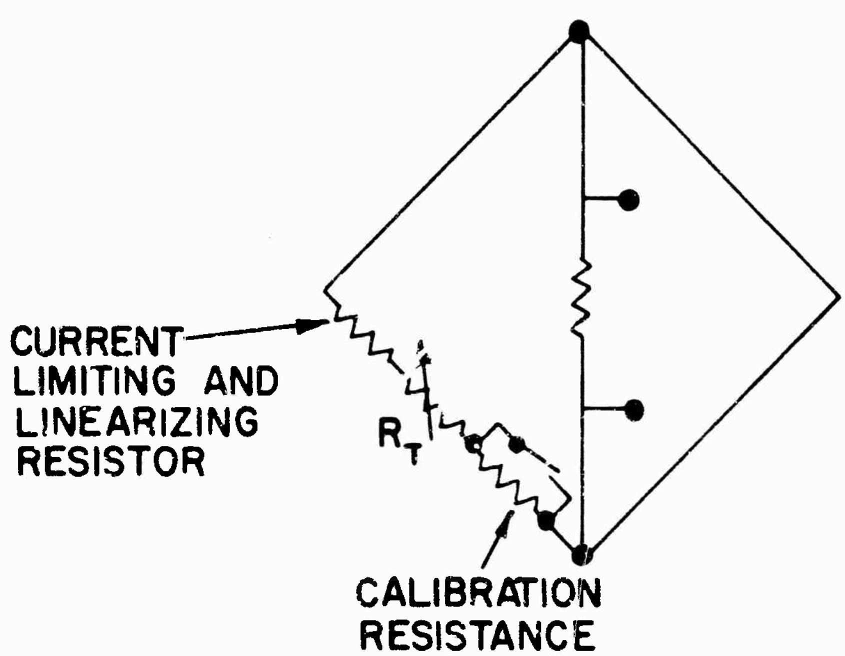

Figure 10. Refined Thermistor Circuitry

Note that calibration is actually done by subtracting the amount desired, since the resistance coefficients of these thermistors are negative. The base or equilibrium resistance usually does not change much and therefore, because the slope of the thermistor curve (see figure 3) also changes slowly, one can often afford to merely use the same base (initial) resistance or even the same slope for several experiments.

2. General Device Configurations

The primary design concern is that the energy be well trapped and converted to heat; another involves thermal isolation of the absorber; a third, equilibrium at measurement time; the fourth, a signal of usable size.

The general design type and the heat capacity are primarily determined by the amount of energy involved.

a. Sphere

The classic blackbody with spherical (hollow) form and small entrance aperture is the basis for a most advantageous design. Suppose the aperture is placed at the focal point of a short-focal-length lens in a laser beam. Suppose further that the hollow sphere is constructed of pure silver or aluminum and the inside surface is polished to a very high degree (by constructing half spheres and joining them after polishing). Finally, the sphere is thermally isolated and a tiny sensor is attached to the surface. A light beam of limited duration entering the aperture will diverge, and, after an initial reflection in which a small portion of the energy is absorbed, the concave surface will distribute the remaining energy in successive reflections. Note that both the sphere itself and the lens outside behave as defocusing agents or lenses, the sphere being in all orientations at once. The aim is for almost all of the energy to be distributed by the light itself, which has the advantage of being essentially instantaneous as well as the big bonus of spreading the absorption process over a large surface area. As the energy, although relatively small, is delivered extremely fast, it can raise the surface temperature of a material above the boiling point if enough of the energy is absorbed over a small area.

Figure 11 gives the general concept of the sphere calorimeter.

The hole should be placed off center, as shown, to limit the return of energy out of the aperture. With a given lens, adapting to larger values of energy involves only increasing the diameter of the sphere as the square root of the energy. Corrections for the lens will be discussed later.

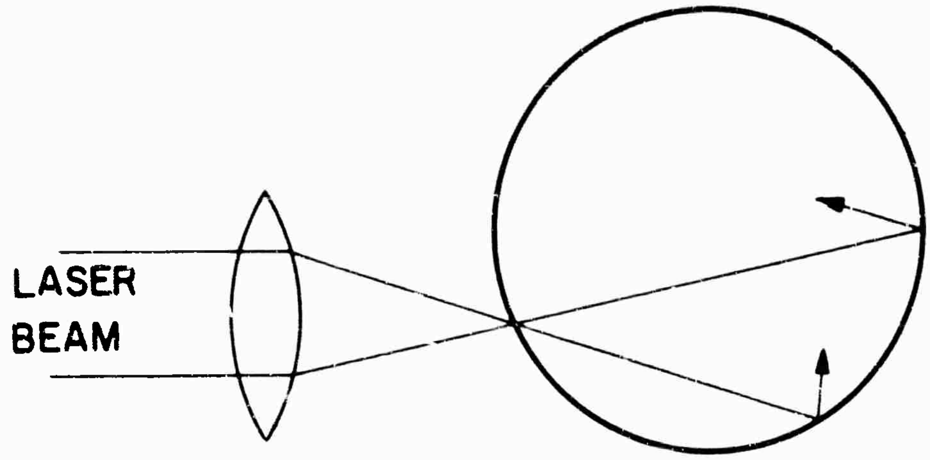

Figure 11. Sphere Calorimeter Configuration

This type of device can be extremely accurate and its simplicity of principle makes it ideal for absolute calibration. The possible lack of simplicity in attendant gear should not discourage those interested in 1-percent accuracies and better.

b. Cone

Another technique, which absorbs any given fraction of the energy in any chosen volume, has the obvious advantage of being less susceptible to local high-temperature rises but implies larger masses. This technique is clearly better suited to higher energies. Since the mass has a solid compact form, it does not need to be isolated as well as the predominantly surface type described before. This results, of course, from shorter average thermal paths and better shielding.

To be taken into account are several items which result in a particular shape for the device. First is the desirability of inducing as rapidly as possible a thermal equilibration. Again, this means that the beam should distribute itself to a large degree. Second, a total energy trap is needed. Third, it is necessary to have a broad enough face to capture the beam without forcing the use of a large volume and hence too large a heat capacity. A conical shape approximates adequately the exponential absorber which would give axial, one-pass equilibrium in the proper absorbing medium. Reflection, beam size, divergence of the beam, etc., all force one to compromise on the single-pass equilibrium goal, but the result is a satisfactory design. Figure 12 shows two possible configurations.

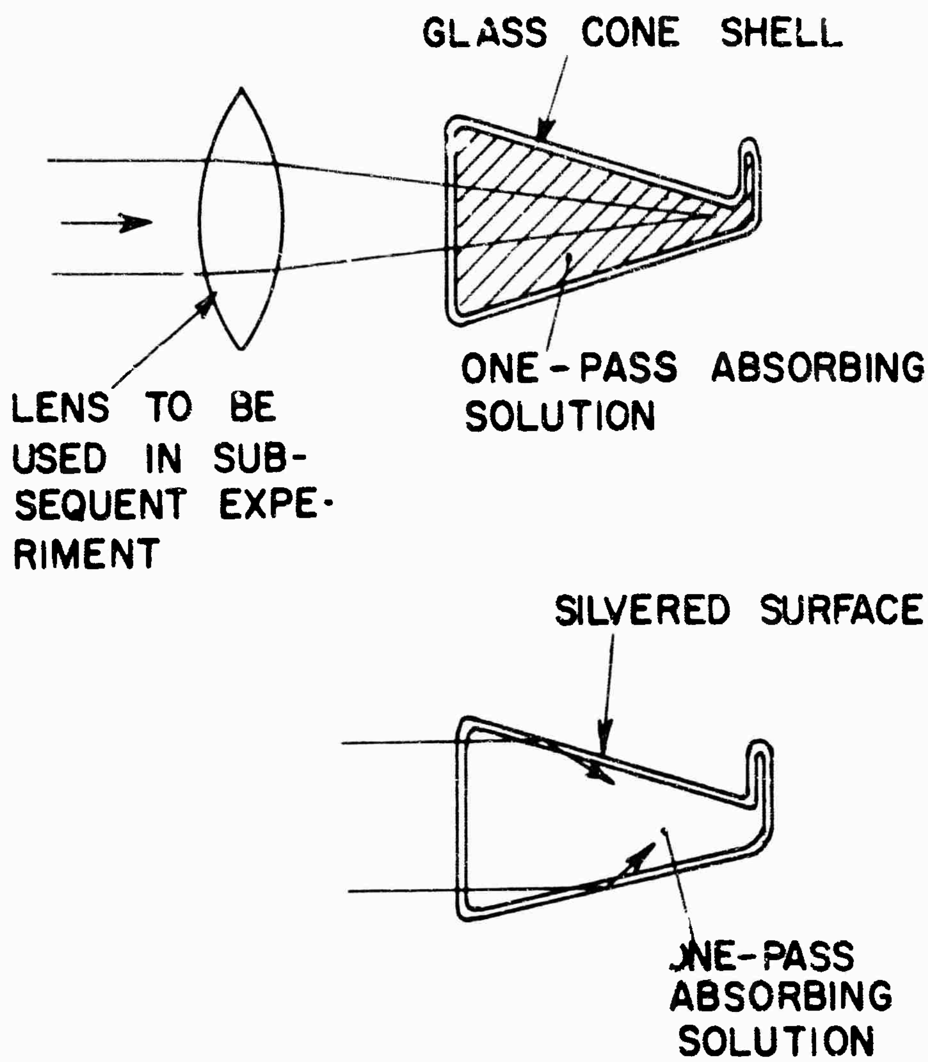

Figure 12. Cone Calorimeter Configuration

A typical cone without really delicate isolation precautions (e.g., no vacuum) will hold a temperature at a decay of less than 10 percent per minute; therefore, one should not be alarmed at the apparent complications. Several thermocouples can be used for higher potential output; this can be a source of sizable error, though, because of heat losses in the leads, and is not necessary. Remember that for each thermocouple on the device, there will be one reference point elsewhere and associated leads.

3. Construction and Performance of the Absolute Device

a. Sphere

The hollow spheres can be constructed as half-spheres using dies of the desired diameter. A 1/2-inch rim or lip on the metal used (generally 0.005-inch-thick pure silver) is rigidly clamped outside the die and then annealed in an oven two or three times during the forming process as it work-hardens. Wrinkles on the lip should be hammered flat on the female die. Metal or silver polish on a soft cloth should also be vigorously applied to each sphere half until it is highly reflective while situated in the female die. Then the lip is trimmed so that 1/16 to 1/8 inch remains. Next, the numbered halves are weighed carefully. Low-melting-point (eutectic) silver solder is used to connect the halves. The lips should be tinned and the halves joined with as little solder as possible. Wide-jawed pliers working on the lips just ahead of and behind the soldering iron will help effectively. Dies and formed halves are shown in figure 13.

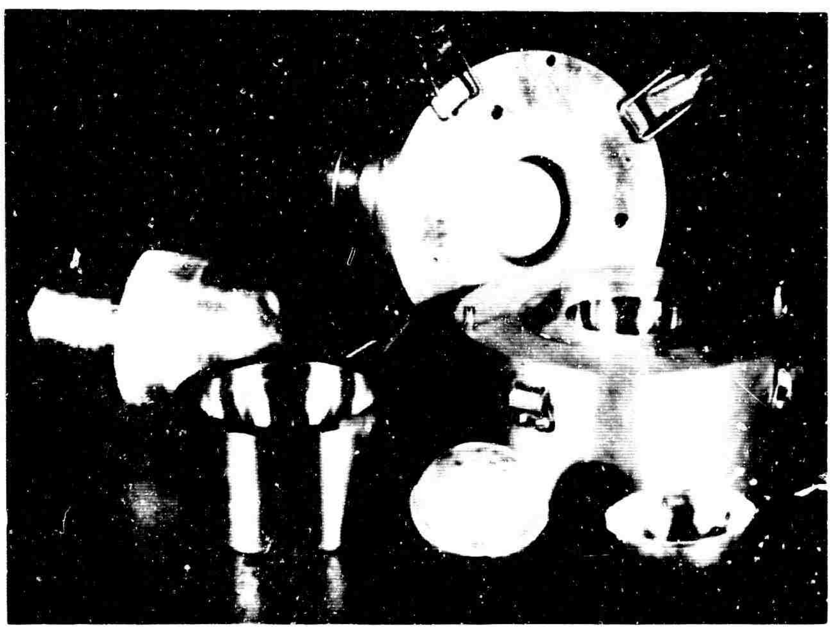

Figure 13. Dies and Sample Sphere Halves

These dies have small oil-exit holes in case a lubricant is used. Finally, the sphere should be weighed, the entrance aperture carefully drilled, three small holes for suspension drilled at equal intervals around the lip, and the sphere weighed again. One then has the heat capacity--the only heat capacity necessary for this measurement. For very fine corrections, it will be found that this capacity varies slightly with temperature.[6]

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[6] Handbook values

To prevent air breakdown at the entrance aperture, the sphere should be surrounded by a vacuum. This is also desirable for minimizing conductive losses. Incidentally, experimental results show that most of the loss is air conduction of the heat.[7] In addition, the vacuum chamber provides a useful sphere and lens support. A sketch of one type of chamber is shown in figure 14.

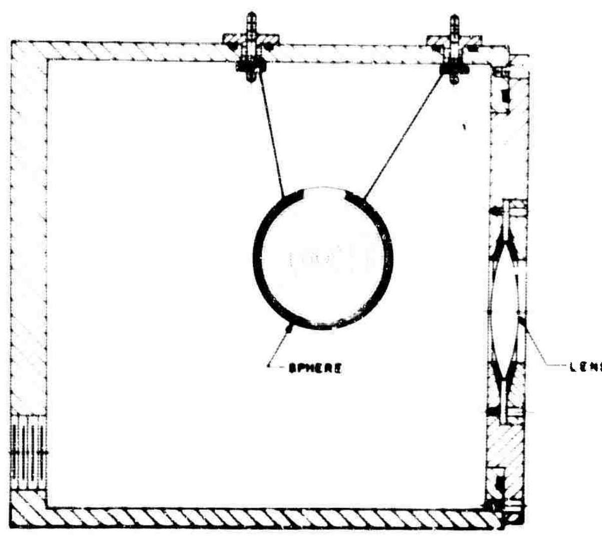

Figure 14. Calorimeter Vacuum Chamber

This chamber is machined from a solid block of aluminum, because good vacuum-tight welds on aluminum are difficult. Electrical feed-through connections with glass and O-ring seals are commercially available. The vacuum connection can, of course, be the type which is standard in the user's laboratory.

Another design, simpler to construct, is shown in figure 15. Essentially, it consists of a pipe and two ends. Each end has an O-ring groove inside the screw diameter.

If for any reason higher vacuums than 0.01 micron are desired, forged aluminum is suggested since porosity is then not likely to be a problem. Generally the thermal conduction begins to recede appreciably (experimentally) at about 1 to 10 microns. There seems little point in going below 10^{-5} mm; if the connections are well made and the overall system is leak free, a high-vacuum, low-capacity mechanical pump will work quite well, e.g., the Welch 1405H Mechanical Pump rated at 0.05×10^{-3} mm ultimate pressure.

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[7]With the device presently being described.

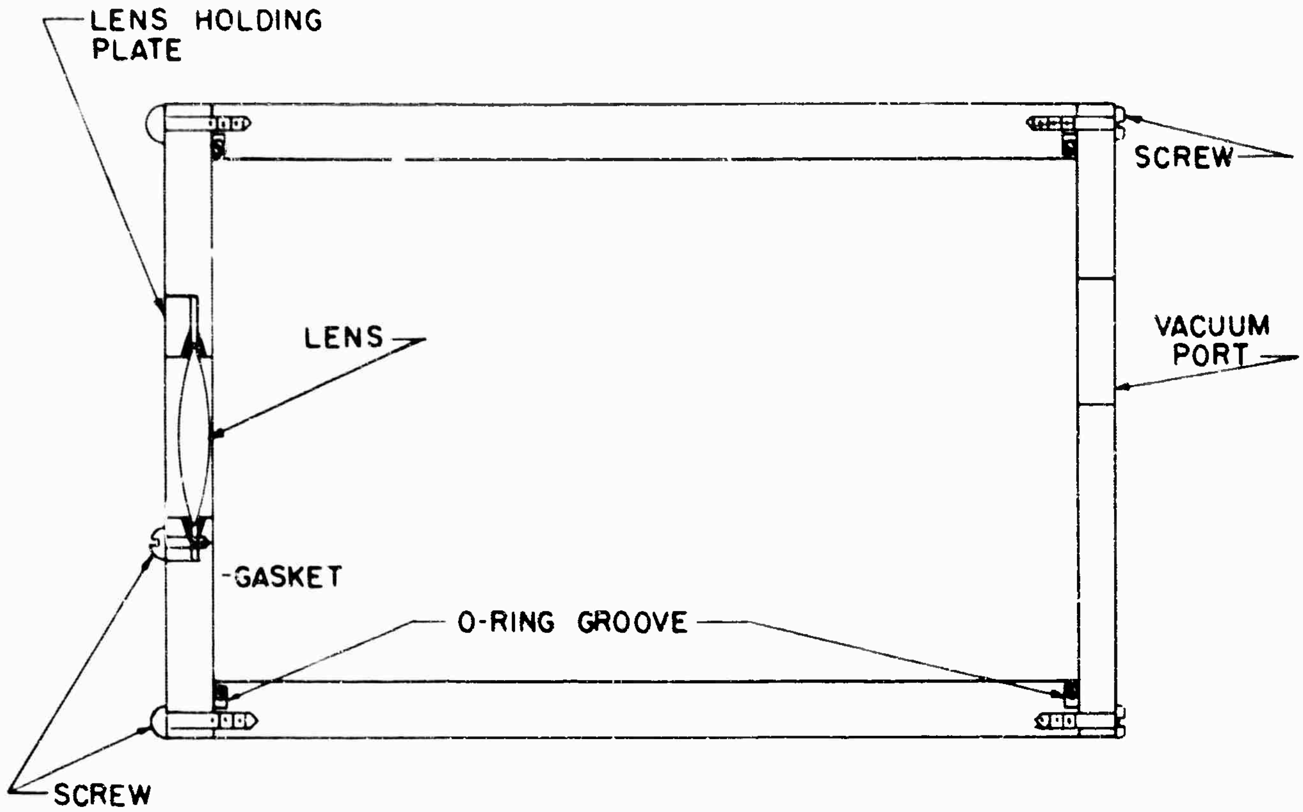

Figure 15. Calorimeter Chamber--Second Design

(1) Suspension System

Two suspension systems have been used. For careful laboratory work, 1-pound-test nylon line is used. This type of filament does not outgas appreciably, it is a relatively poor thermal conductor, and it is readily available. Three nylon leads are attached at one end to the three holes in the sphere lip, and at the other end to a simple Teflon frame which allows positioning. Figure 16 illustrates this suspension.

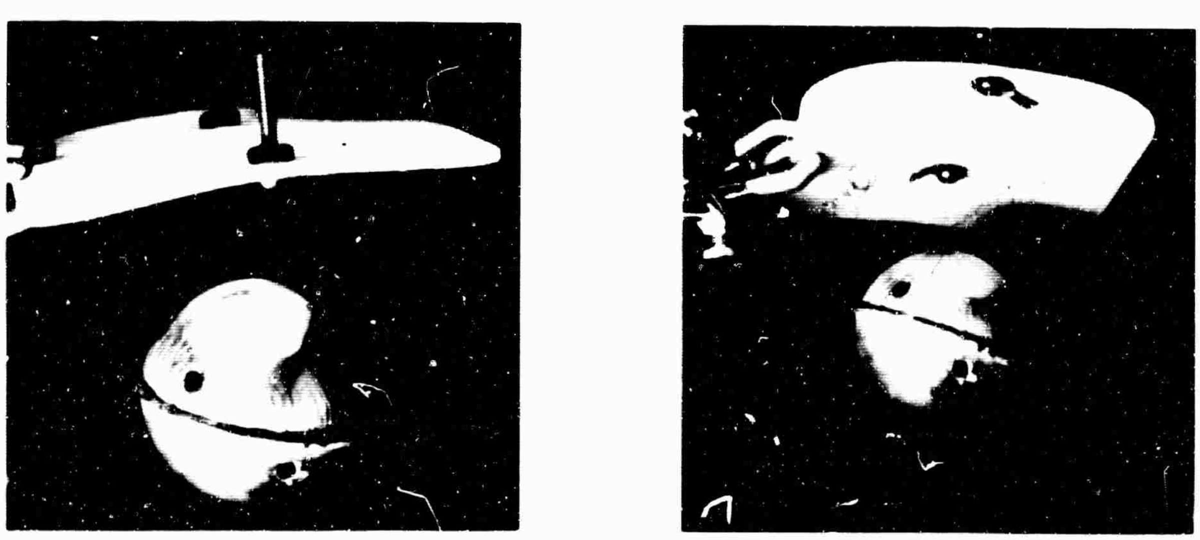

Figure 16. Finished Sphere

Notice that this arrangement allows removal of the entire unit from the chamber. Notice also the nylon leads which hang down in the chamber for the adjustment. It is necessary to coil the copper lead wire to prevent thermistor lead breakage. The thermistor leads can be connected to the copper wire by making a small overhand knot in the copper wire to hold a meniscus of melted solder. The thermistor wire can be inserted in this and a tight fit will result when the solder hardens. It is not clear that the thermistor is actually soldered, but the connection can be excellent, probably because of difference in thermal expansion coefficients.

The thermistor should be attached as follows: An adhesive which has good thermal conductivity and good electrical resistivity.[8] With as little glue as possible, place a thin patch on one side of the sphere (looking toward the hole) about half way up. When the glue dries, separate the thermistor leads; place the thermistor on the patch and cover the thermistor and a small amount of lead on each side with a bit more adhesive. If the size thermistor illustrated in figure 7 is used, the added heat capacity will be negligible.

Under less than ideal conditions, a rigid suspension can be used as shown in figure 17, and a larger entrance hole drilled (in this case about 3 mm and in the laboratory case 1 mm). This frame is also Teflon because of its relatively low thermal conductivity and vacuum characteristics. The support contacts made with the sphere should be as small as possible.

The entrance aperture is centered by rotating the sphere on its off-center mounts. The distance from the lens is set with nuts on threaded rods through the locating disc. Thermal loss rates via the mounting are greater but are still very small compared with the rise rate. To simplify further, thermocouples might also be used.

The initial signal depends on the location of the sensor, but at equilibrium it will be the same everywhere on the device. For example, consider a typical response and suppose that sensors are placed in different

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[8] One which fulfills this requirement (80% steel, about 50 mm) is called Plastic Steel; Devcon Corporation, Danvers, Mass.

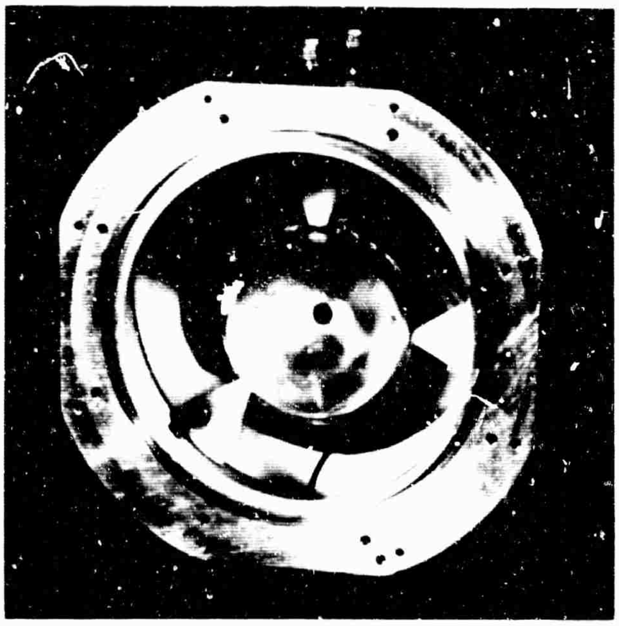


Figure 17. Mounted Sphere

locations. On a plot such as figure 18, there would be an infinite family of curves between (a) and (b) amplitudes and between zero and t_1 times. If the sensor is placed in the most neutral position, i.e., the position whose curve is lowest in the family, (b), the signal is least confusing and tells approximately the true time for equilibration. It is not difficult to visually determine this position nor is the position apparently very sensitive on a sphere. The reason is, of course, that most of the distribution is done by the light beam.

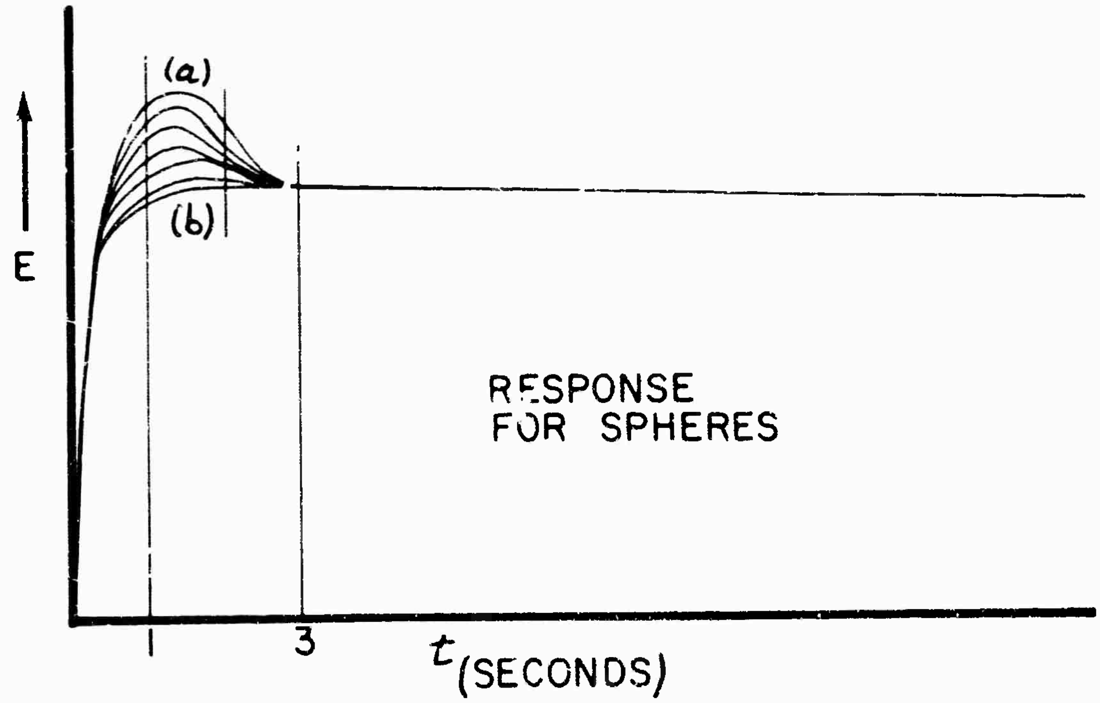
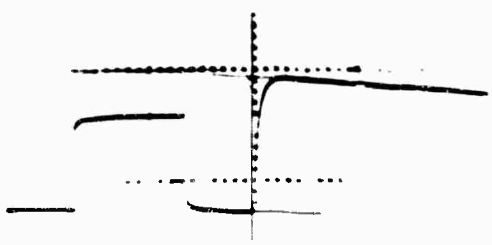


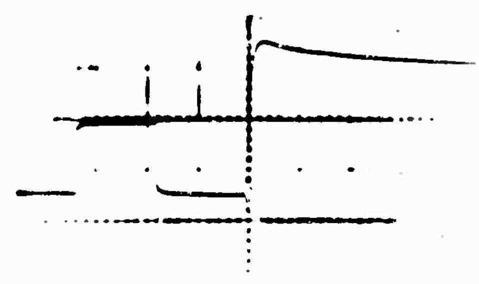
Figure 18. Temperature Response Curves

(2) Correction

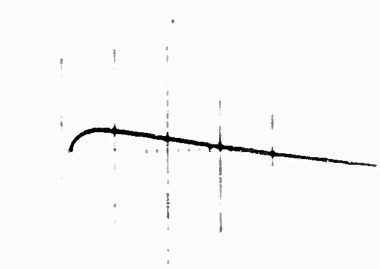
Though relatively short times are involved for equilibration, heat is lost in the process. First in the correction one wants to ensure that local "hot spots" do not cause larger loss rates than the equilibrium rate. With these designs, the initial rise is internal and thus radiation or conduction loss rates much greater than that at equilibrium are prevented. The great simplification to this correction results from relatively instantaneous arrival of the energy. It can therefore be said that the energy arrives at time t_0 and thereafter losses are not complicated by gains. Figure 19 shows typical sphere temperature behavior.



a. (time)



b. (time)



c. (time)

Figure 19. Temperature Response Traces

Traces a. and b. were recorded at 1 micron vacuum; trace c. was recorded in air. Note slight "hot spot" in trace b. The correction is an extension of the decay to t_0 as shown in figure 20.

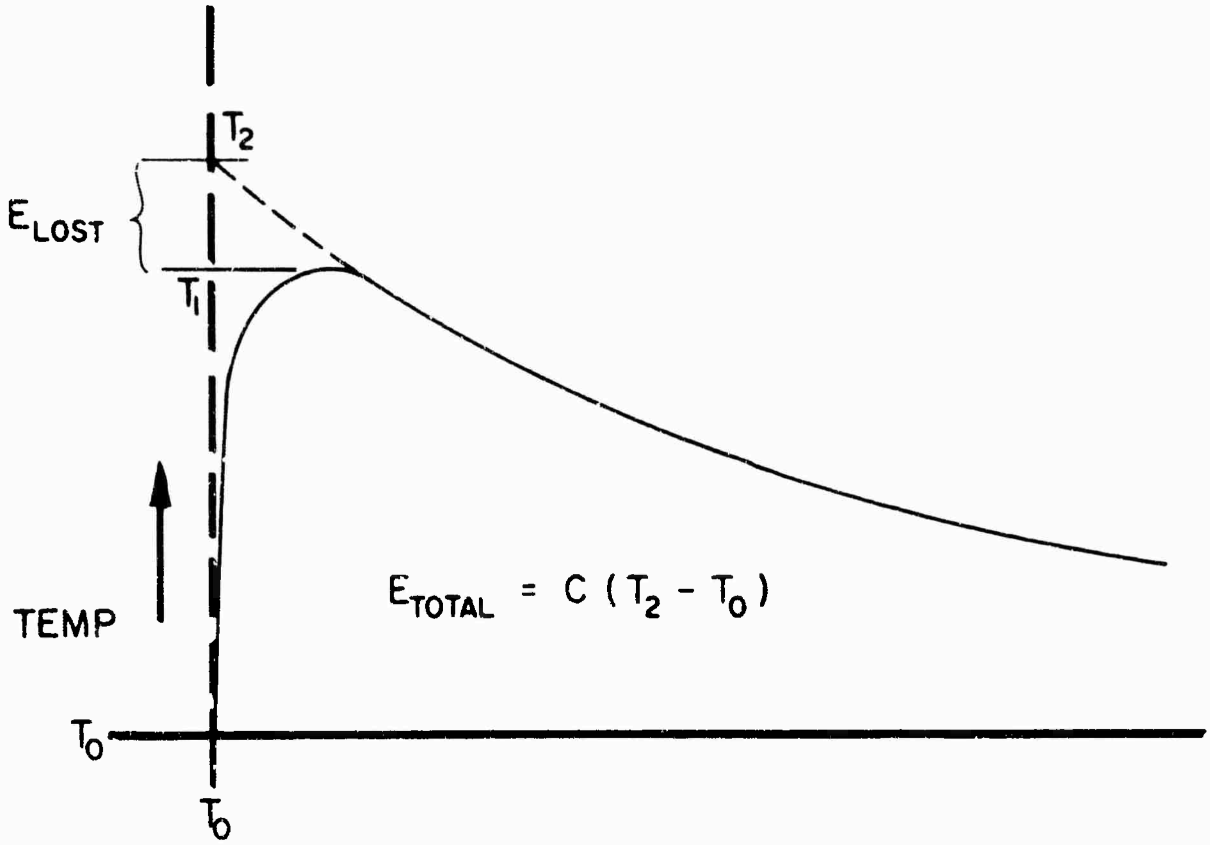


Figure 20. Temperature Decay (an exaggerated case)

One would need no correction in either of two cases; first, if the rise to equilibrium were instantaneous and, second, if there were no decay. If better accuracy is needed (about 0.1 percent and better), then further steps can be taken to improve on these two. This correctional treatment can be applied to the cones as well.

The lens attenuation involved in the calibration must be accounted for. The fraction of energy that is not transmitted through the lens can be calculated, checked on a spectrophotometer, or, still better, can be determined in the beam. The last technique assumes that lenses of the same general characteristics have the same reflection and absorption properties, corrections for which can be made if needed. It should be noted that since to begin with we are making a correction, a 5 percent error in these connections should be less than 0.5 percent of the total measurement. Figure 21 shows the physical arrangement. The resultant calibration will resemble that in figure 22.

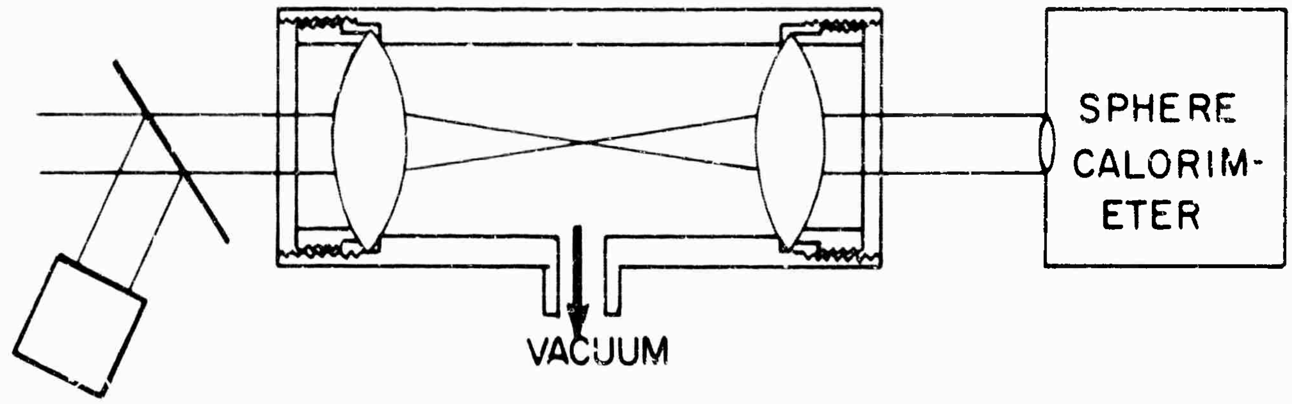


Figure 21. Lens Loss Correction Configuration

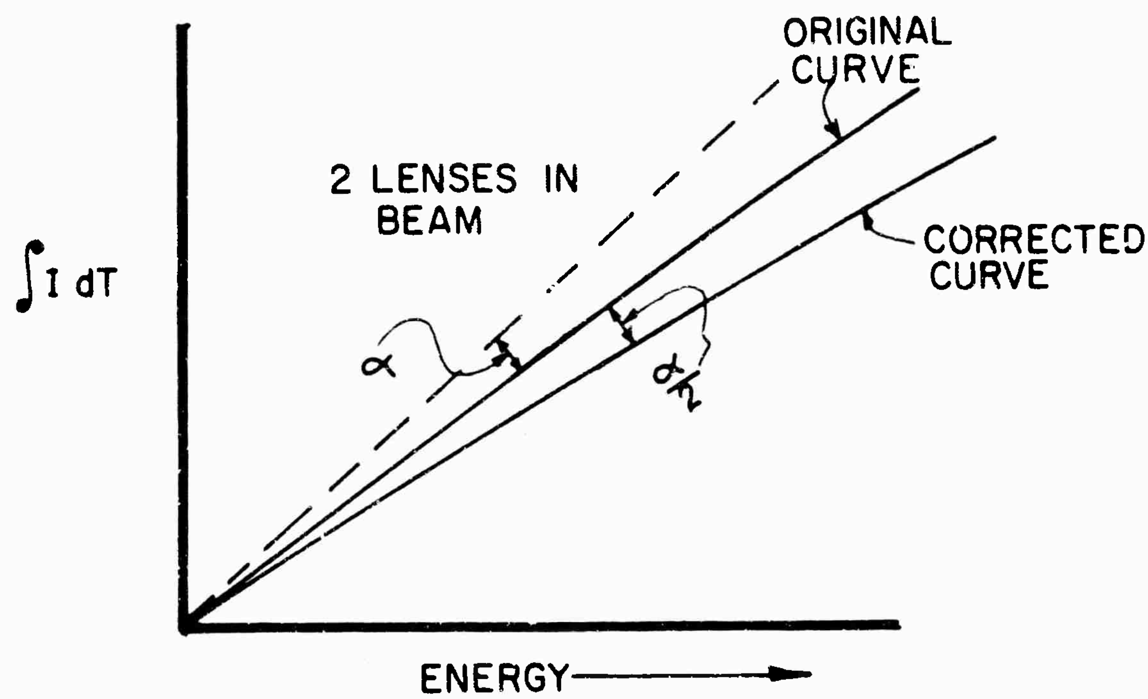


Figure 22. Lens Loss Correction Curve

The vacuum between lenses, once again, prevents ionization of the air at the focal point.

b. Cone

The volume absorption cones are constructed of Pyrex glass with a fused-quartz front plate and filled with a solution of copper sulfate and water such that absorption of about 90 percent of the beam is obtained on the first pass. The Pyrex part is fabricated by a glass blower from pieces of conveniently shaped laboratory glassware. Front plates are optically flat fused-quartz plates.[9] The fused-quartz plate is attached to the Pyrex cone with epoxy, which can be removed if the plate becomes damaged. A boiling solution of acids (3 parts concentrated nitric acid, 1 part concentrated hydrochloric acid) will remove the epoxy without damaging the glass.

Figure 23 shows some of the bare cones. The small stopcock easily allows variation of the C_uSO_4 concentration.

Figure 23. Sample Bare Cones

Construction starts with roughing the quartz disc and the forward edge of the cone where the two make contact so that a good epoxy bond will result. This can be accomplished with emery paper. The finish of a glass saw cut is sufficient to surface the edge of the cone. (Incidentally, the first few cones were made at AFWL by quite inexpert glass blowers, yet gave satisfactory results.) When the plate is attached, the cone should be plated with aluminum or silver. A vacuum plating setup is shown in figure 24.

[9] Good fused quartz is about the best material available to date for withstanding high-power energy of beams.

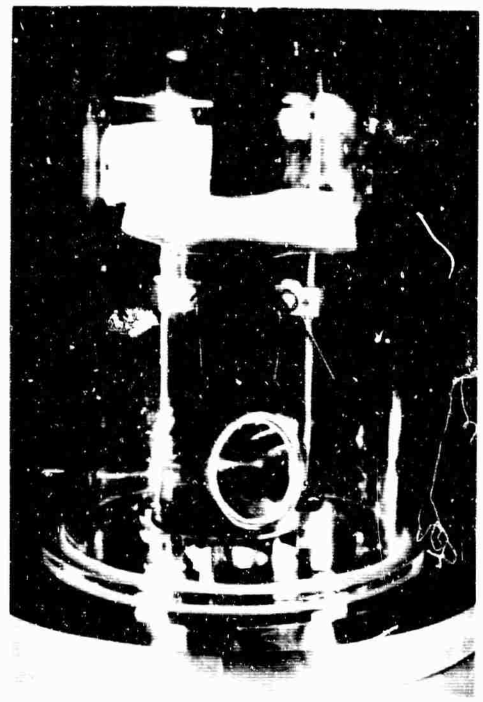


Figure 24. Vacuum Setup for Plating Cones

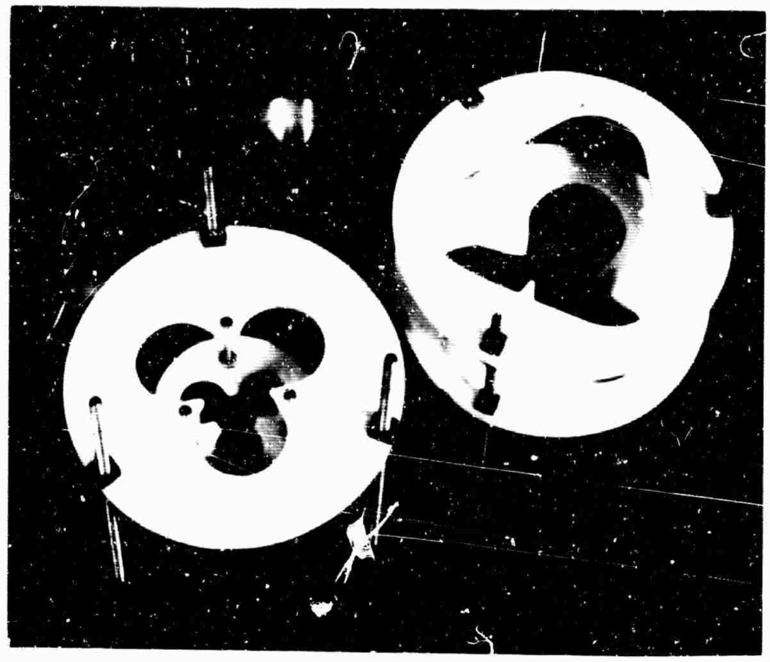
In practice, the bell jar has a Teflon insert (easier to clean than glass), and the plating process is observed through the bell jar top by placing a piece of glass in the bottom which then becomes coated and reflects the filament or object.

When the plating is complete, the surface of the cone may be sprayed with clear lacquer for protection.

Next the cone must be filled with the absorber. This can be easily done with a hypodermic needle. Space for a fair-sized air bubble should be left in the tube on the cone. The tube must then be sealed. A stopcock, such as shown in figure 23, or a small section of rubber stopper pressed in and covered with epoxy will do. Until the epoxy hardens, it should not come in contact with the solution, since this would result in a weak bond. If the cone is to be placed in a vacuum, the seals must be especially well made because the pressure differences are fairly large. As previously mentioned, a vacuum environment is far less important with cones than with hollow spheres. The sensor is attached to the outside in the midsection of the cone.

Mounting frames for cones of two sizes are shown in figure 25 (a) and a mounted cone is shown in figure 25 (b). The reference thermocouple is mounted between two corks which are obscure in the picture.

With the two types of devices described, one can measure energies from less than 10^{-3} joule to almost unlimited values.



a. Cone Frames

b. Cone Mounted

Figure 25. Cone Frames and Mounted Cone

SECTION III

THE RELATIVE INTEGRATED MEASUREMENT

1. Direct Type

The direct type of measurement will be discussed first, that is, one that does not initially require a time-resolved signal. The idea is to obtain as simple a device as possible. The requirements are, first, a smooth, single-valued variation relative to the absolute device (not necessarily linear) and second, the relation must be as precise as required. The resulting device, as described below, was originally designed as a stand-in for another type but has proved quite satisfactory in the present application.

The angle of alignment and the position of the device in the beam are critical with many devices. It is desirable to reduce this dependence. A readout as simple as possible is also desired. The signal must be taken from a sampling of the whole beam cross section, which will in general consist of a rather small amount of energy. A small heat capacity is necessary if the usual heat sensors are to be used.

For higher powers it appeared that a diffuse foil with a somewhat reflective surface would be best; hence a diffuse thermal conductor (aluminum foil) was used. Silver and similar materials do not maintain surface appearances and thus are not suitable. The aluminum foil is not too sensitive as to angle. To isolate it the foil is suspended in dead air. It will simplify the readout if the energy decay is not too rapid. However, no particular value is needed here, so a maximum can be chosen. A typical trace from this device is shown in figure 26.

The value "A" is as good as any for comparison with the total energy. An exploded view of the foil bolometer and a photograph are given in figure 27. Usually the "foilometer" is enclosed in a metal case which has a filter rack in front of it. (Neutral density filters and band pass filters 2 in. x 2 in. are used to ensure suitable laser signals and to exclude the pumplight.) Again a thermocouple and its reference can be used. The signal thermocouple is mounted on the rear center of the foil. The reference is

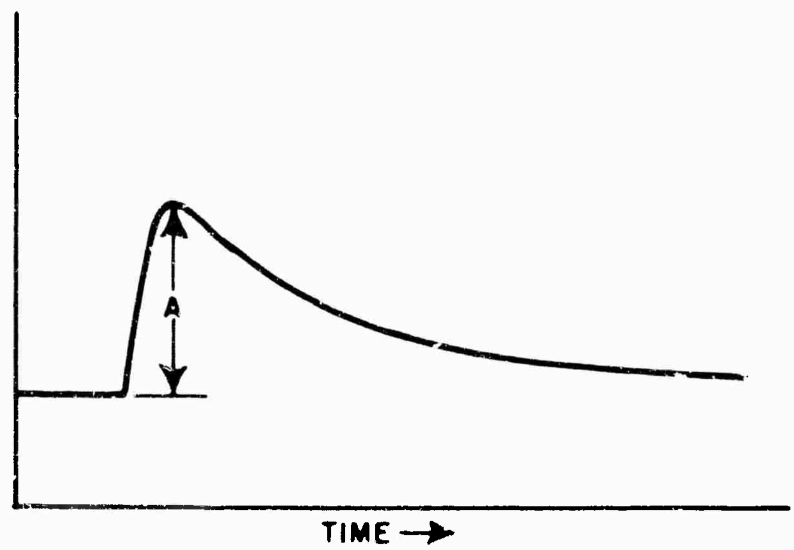
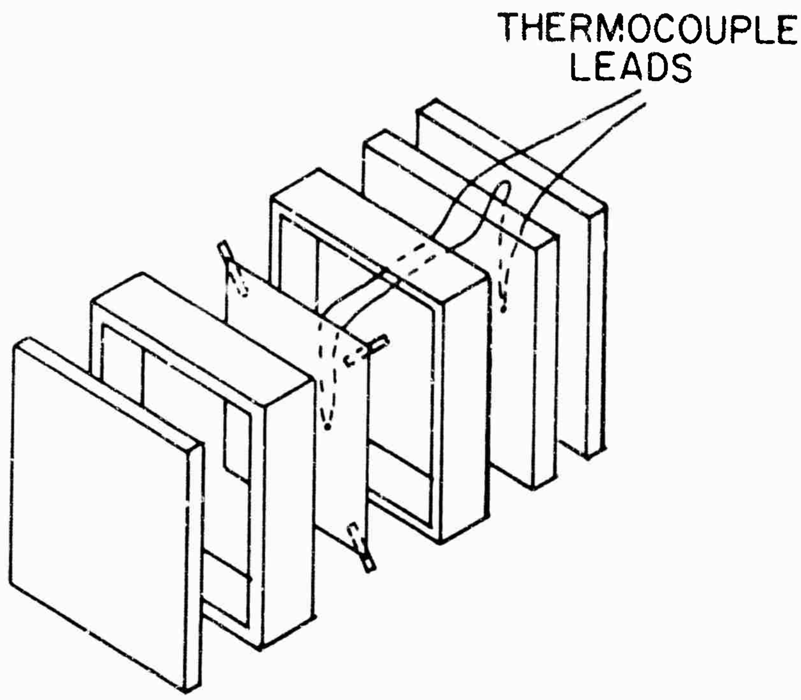
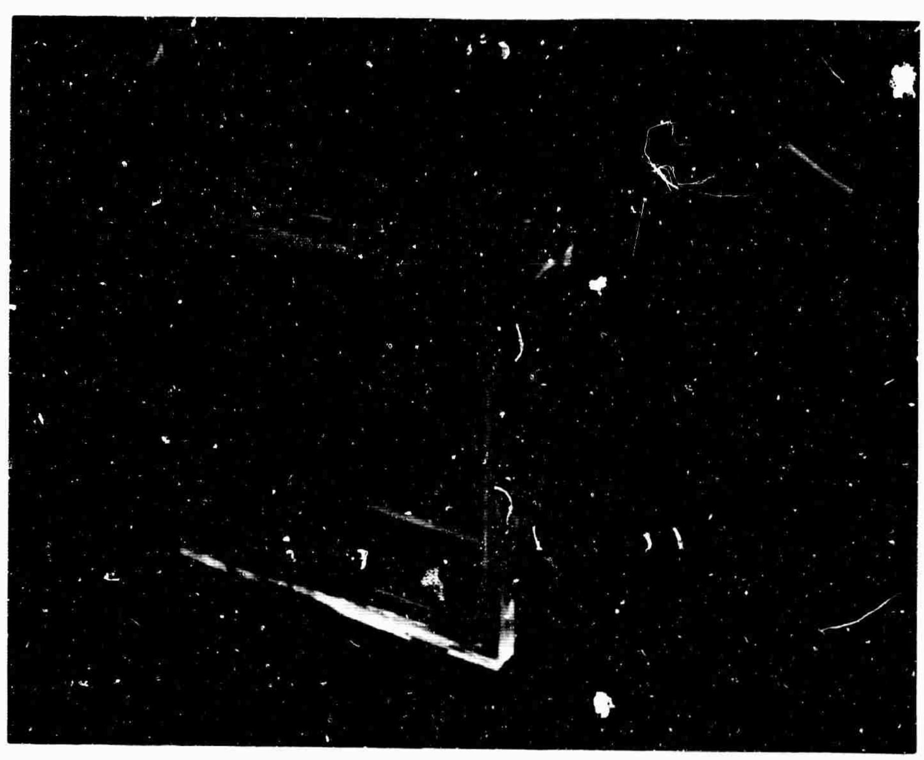


Figure 26. Bolometer Response



a. Exploded View



b. Assembled

Figure 27. Bolometer

cemented between two thick pieces of plastic as isolation from the laser beam, and the heat caused by the flash lamp. There does not appear to be any problem of drift. The two thermocouples settle within 10 microvolts of each other and usually maintain this with less than ± 2 microvolt drift per minute. All such signals are passed through a low-frequency-response dc chopper amplifier so that not noise but drift is a real concern when designing the device. This stability, however, is typical of the thermocouple setups used for any of these measurements. The thermocouple leads should have as few external connections as possible.

2. Platinum-Wire Bolometer

A device more difficult to construct, but whose spatial sensitivity is further reduced, consists mainly of a thin plate of electrical insulator around which is wound close parallel turns of platinum wire. An essentially opaque mixture of epoxy and carbon granules then bonds the wires to one face of the thin plate. This layer should be as thin as possible in order to limit the heat capacity and therefore maintain sufficient signal amplitude. Figure 28 illustrates this device.

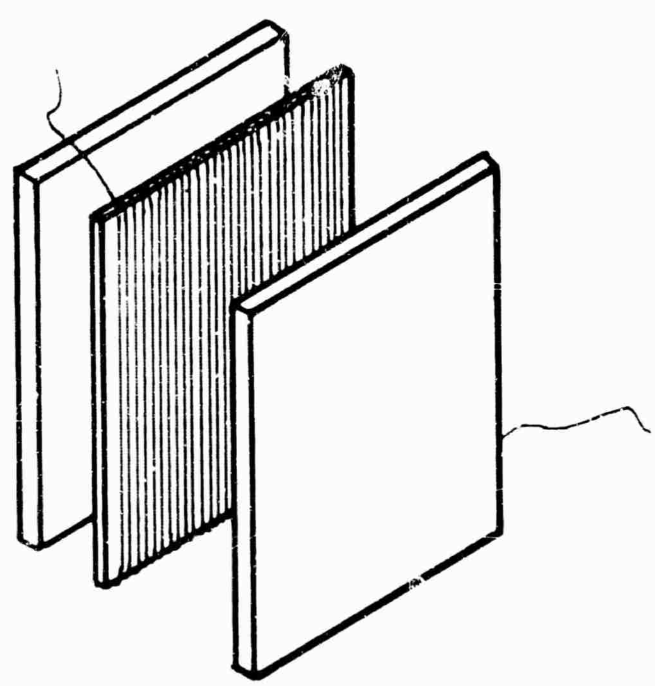


Figure 28. Platinum-Wire Bolometer (exploded view)

The figure omits the needed frame pieces that provide a dead air space around the bolometer. Platinum wire will be nearly linear over the temperature range involved (less than 10 degrees, and for lasers in the region of 10 joules, about 1 degree). As with thermistors, the amplified bridge signal provides a suitable output. The thin plate should be mounted in a dead or isolated air space as was the foil bolometer. Other variations on this theme may better suit particular needs.

3. Integration of Phototube Output

Electrical integration of a time-resolved signal does not involve detailed mechanical construction for the experimenter, though the validity of the measurement is then contingent on the performance of the photodetector and circuitry. This is discussed in the appendix. The basic problem concerns instability in time and spatial sensitivity variation across the cathode of the detector used. The sensitivity problem can be minimized by utilizing the whole photocathode, and the degree of precision obtained in calibrating the systems using this technique may prove to be sufficient.

The integrator [illegible] are now discussed. Detector operation is discussed in the section on time-resolved signals.

a. Integrator Concept

In one scheme the detector draws a current which is proportional to the intensity; this current ultimately removes the charge from a capacitor plate, which causes a voltage that rises proportionally to the number of electrons removed. The recording device should have an extremely high input impedance in order that the potential on the capacitor may not be depleted too quickly to read. The basic unit involves only a capacitor; its operation is diagrammed in figure 29.

Sophistications include a diode to prevent reverse current, a resistor to ground to ensure that the potential starts at zero, and a current-limiting resistor to prevent the capacitor voltage from approaching that of the detector power supply. See figure 30.

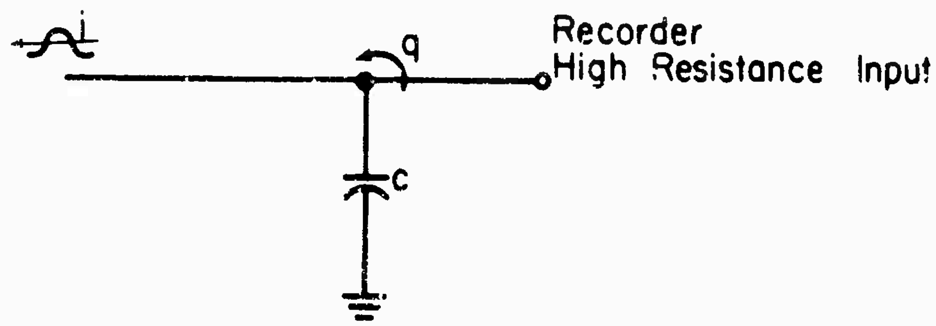


Figure 29. Basic Integrator Circuit

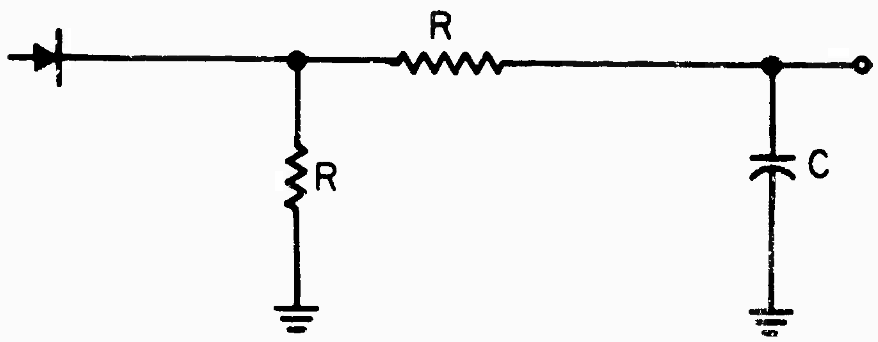


Figure 30. Complete Integrator Circuit

This integrator works for both long and short pulse operation although the values may need changing for best signal amplitudes. Raising the values of either R_2 or C will proportionally lower the output. R_1 is, in dc terms, a leak, and in ac terms, part of a voltage divider. Its value is typically 10 megohms with scope readout. With scope readout, other parameters are typically R_2 = 100 kilohms, C = 0.05 microfarad, time base is 1 millisecond per centimeter, input impedance is 1 or 10 megohms, and trace amplitude is of the order of 1 volt for low-energy lasers. As with any such relative measurement, one need not read the integrated value corrected to event time t = 0. The maximum value will do. Cable length, cable type, or component values including input impedance of the recorder should not be altered once calibration has been performed. An integrator trace is shown in figure 31.

Figure 31. Integrator Trace

The time-resolved and integrator signals should not generally be taken from the same detector. Time-resolved circuits are designed with low-impedance lines and loads to pass the current from the line (cable) which tends to act as a capacitor, integrating through the load to keep pace with the signal. The integrator cable should be terminated in a high impedance; therefore a large protion of the current would be reflected. It would then appear in the time-resolved portion of the network, including at the load. If one is working with a short pulse and the reflection is kept well away from the real pulse in time (with respect to oscilloscope), the same detector might be used, since the integrator output would not be confused by this signal. Long signal cables will perform this function.

An electrometer has also been used to read the voltage across the capacitor, without much success. According to a firm which manufactures an integrator-electrometer unit,[10] the electrometer used, a Kiethly, dumps fast signals via an internal impedance change which presents itself to a pulse at the input.

b. Galvanometer Concept

A second scheme involves the use of a ballistic galvanometer. It may be inconvenient to read but it is a common item in the laboratory.[11]

As a bare minimum of equipment, the number of devices looking at the output can be reduced to one for relative energy measurement and (for calibration) one for absolute energy measurement. If the pulse shape is consistently the same, then the maximum height may be related to the total energy value and no integration is needed. If, on the other hand, the pulse shape is not the same for each shot, a planimeter can be used to integrate the area under the curves. Several companies manufacture small planimeters practical for reading scope traces, or translucent graph paper with fine grid lines can be superimposed on the signal trace and the squares counted.

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[10] A specially modified unit was tested in this application at AFWL. The manufacturer is the Geophysics Corp. of America, Bedford, Mass.

[11] AFWL has used a Leeds and Northrup galvanometer #2285D (Sens. 3 x 10^{-4} μc/mm, period 27 sec) light, and scale for this purpose.

SECTION IV

THE TIME-RESOLVED MEASUREMENT

In general, the requirements for the time-resolved detector are high-speed, undistorted response to the signal, and sufficient output to be recorded on high-speed oscilloscopes. Time and signal requirements for today's shortest pulses are typically 1 nanosecond or less total time distortion and 10 to 20-volt signals across 50- or 125-ohm loads. Slower pulses have less stringent requirements. The photoelectric type of detector will satisfy these requirements with additional benefits. The ideal detector would be one which would accommodate the whole beam face without requiring beam focusing. Amplification of the light signal (either internally or externally to the detector) is generally not necessary or desirable, even when a small fraction of the beam is sent to the detector. Amplification merely adds distortion. For example, consider a square pulse (for convenience) of 10^{-8} second duration with total energy of 1 joule. Suppose the combined attenuation and sampled percentage gave 10^{-5} of the total intensity in the detector. Set the quantum efficiency of the photocathode at 0.1 percent, although it will inevitably be higher. The calculated current output is about 0.5 ampere and the voltage is 25 volts across a 50-ohm load, a more than ample signal without amplification. The response requirement suggests a detector design. High electric fields between the anode and the photocathode will aid fast response. Distortion due to geometry also comes under the heading of response problems. The parallel flat plate configuration seems ideal. Electrons which leave the photocathode have different initial speeds and directions of travel. In the parallel plate case (illustrated in figure 32), the field can be made large so that the photoelectrons tend to travel normally between the plates. Also discrepancies in initial speed are made less significant when they are accelerated beyond the initial speed. The parallel plate idea then minimizes response distortion while allowing large cathode areas.

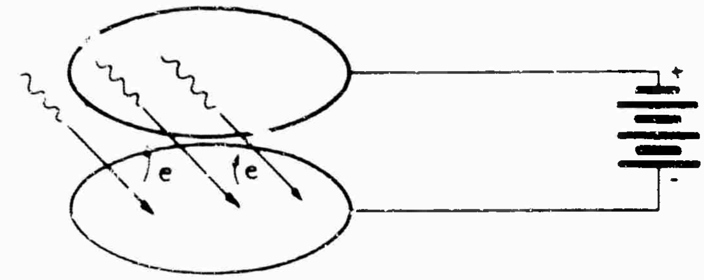

Figure 32. Parallel-Plate Photodetector Circuit

A representation of the limits of distortion due to different initial photoelectron speeds and directions of travel is shown in figure 33.

These curves represent the envelopes of possible photoelectron trajectories for several field values. Resultant time distortions are plotted along the vertical axis above plate (a). The work function is taken as zero because of the variation with cathode surface material; hence, this indicates the maximum possible arrival variation.

Several years ago, a series of tubes was developed (along these lines) for use on nuclear test shots. These tubes[12] have screen anodes so the beam can enter normally on the photocathode. Photocathode diameters range from about 0.5 inch to about 5 inches. The general geometry suggests that the output be arranged in the form of coaxial cylinders whose ratio of diameters can be changed behind the photodiode to match the impedances of the readout oscilloscope. If one recalls the math involved in the microwave matching problem, an exponential taper that is long compared with the effective wavelength of the pulse, is a valid matching scheme for fast pulses. The solution with regard to even very fast pulses dictates tapers that are too long to be practical. However, if the transformation takes place very close to the tube and the output line is well terminated at the readout end, there is very little distortion or reflection, nor do lower frequencies appear to be appreciably attenuated.[13] On the most popular of these tubes,[14]

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[12] ITT Components and Instrumentation Laboratory, Fort Wayne, Ind.

[13] Exponential tapers attenuate at low frequencies (function of taper length).

[14] The FW114, outside diameter 2-1/4 inches, cathode connection 1/4-in. dia.

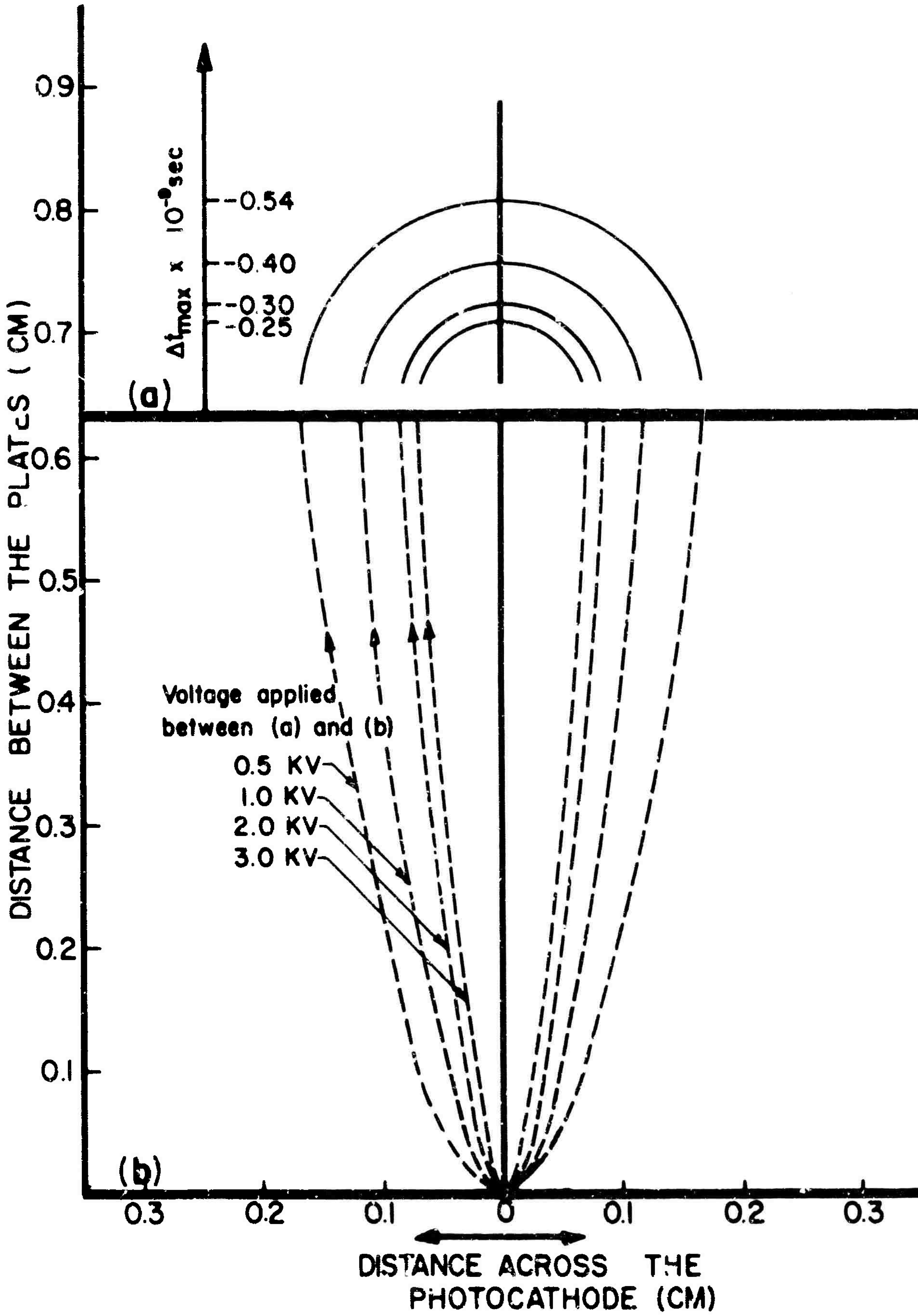

Figure 33. Electron Trajectories in Vacuum Phototube 7,000 Å Light

the "natural" coaxial impedance by the common high-frequency relation[15] is about 130 ohms. so the output impedance, and hence the ratio of radii, will not require large changes but both radii will need to be reduced to connect with cables. A housing to match the diode to line is sketched in figure 34.

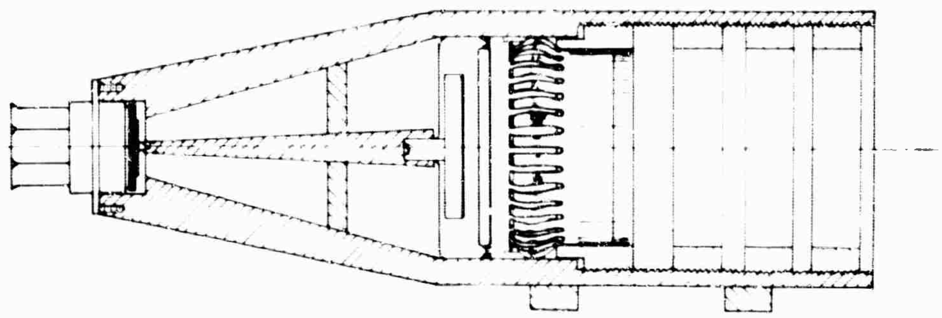

Figure 34. Diode Housing

This housing has interchangeable tapered inserts for different impedance outputs; some of the hardware involved is displayed in figure 35.

Figure 35. Diode Housing Assembly

15

$$Z = \frac{\sqrt{\frac{\mu}{\epsilon}}}{2\pi} \ln \left(\frac{\text{anode outside radius}}{\text{cathode output radius}} \right)$$

The locating disc on the tapered rod is Teflon. At the left of the figure is shown a 125-ohm insert for the General Radio type GR-874 connector This type of connector allows disassembly and either of two sizes of center conductors and insulators can be installed. For subnanosecond response, at least two single-event recording scopes are available, one with 50-ohm input and one with 125-ohm input.[16] Tektronix makes 125-ohm inserts for the GR-874 as well as attenuators, terminators, 125-ohm cables (RG-63), etc., for their 519 system.

To set up the field necessary for fast response and for operation in the region of proper tube characteristics, a voltage must be applied across the plates. For safety and convenience, this should be applied to the cathode (negative) and the shell can be grounded. Components for the time-resolved detector should be placed in the signal line and near the detector. Refelections are thus minimized by the former precaution and placed closely within the signal by the latter. It is not practical to attempt powering such a fast pulse detector with electronic power supplies. First, there is the difficulty of ensuring adequate current. Second, as high-speed demands are made on it, the impedance of the supply will certainly change. Regulated supplies would probably be most troublesome in this respect. At any rate, a capacitor is much better suited to the task. The negative supply voltage applied to the photocathode does not, of course, determine the final signal voltage appreciably unless the supply voltage falls below a certain minimum (figure 36).

The V critical marks the border below which charge builds up between the plates to some degree. Therefore the capacitor is charged and the charging unit isolated during the event; i.e., a large resistance in the lead of the charging unit near the detector limits the current so that it is essentially not seen during the pulse time. The schematic is given in figure 37.

A photo of the system of diode and components is shown in figure 38. This shows the time-resolved signal system minus scope, charging unit, and lines. A beam splitter is shown on the input.

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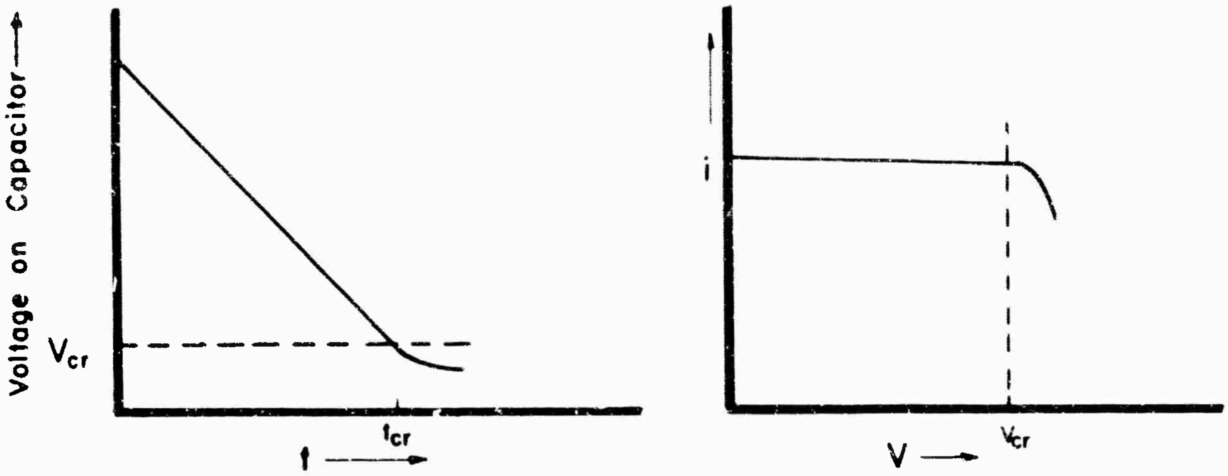
[16] 50 ohm--Edgerton, Germehausen & Grier, Traveling Wave Tube Scope
125 ohm--Tektronix 519



a. Capacitor discharge with time (assume a square-shaped light pulse)

b. Current output with voltage

Figure 36. Capacitor and Current Traces

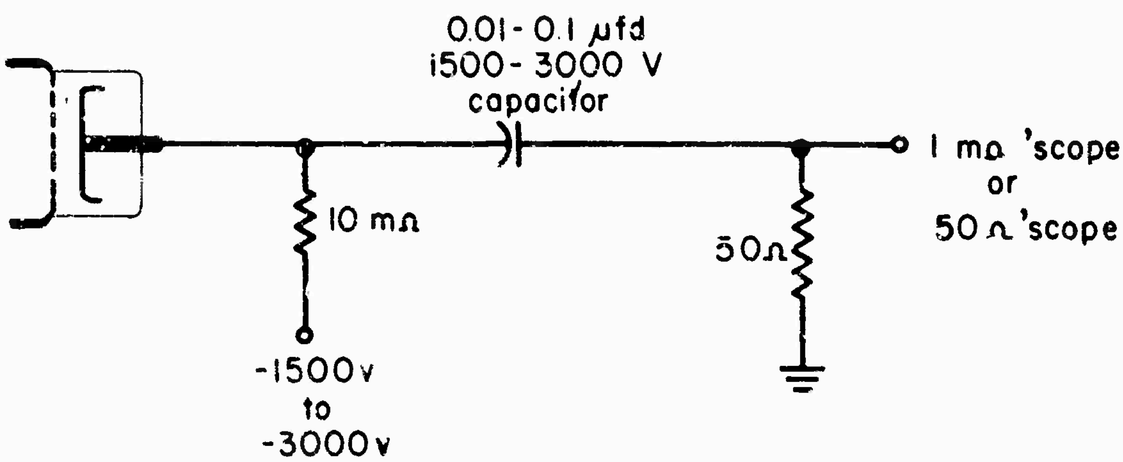


Figure 37. Diode Circuit

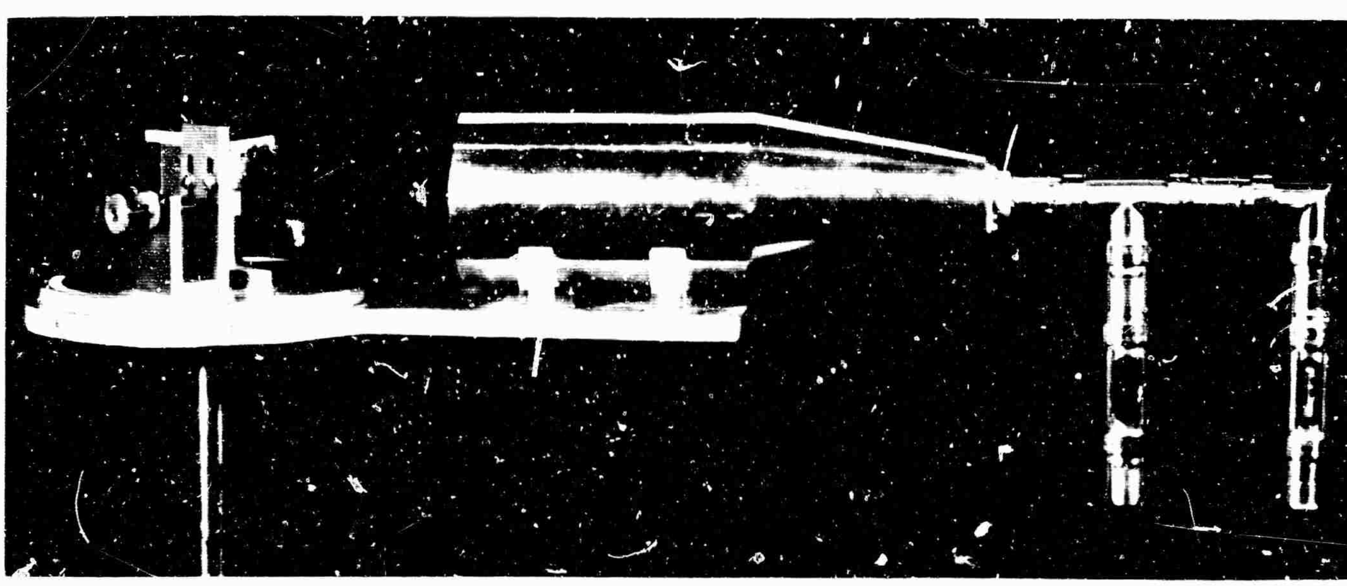


Figure 38. Diode Mounted on Beam-Splitter Platform

Spatial resolution of the beam could be accomplished by using simpler and much smaller time-resolved detectors[17] or fiber optics and detectors. Relative integrating devices could be constructed of small segments, each with its own sensor, if integration of the time-resolved signal did not work out. Thermocouple junctions might be potted in small epoxy slugs in which are mixed fine carbon granules. These could then be assembled (or potted) in the same pattern as were the time-resolved detectors. The line-up should not be too difficult if a collimated light beam can be passed through the system.[18] A "pointer" or aperture inserted in the beam should coincide on both patterns.

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[17] a) CP-1 Laser Detector, CBS Labs, High Ridge Road, Stamford, Conn.
b) L-4500 Diode, Philco Corp., Lansdale, Pa.

[18] Compact gas lasers are now on the market and are ideal for laser and instrumentation line-up.

SECTION V

THE SYSTEM

1. Typical Systems

The construction of mountings and adjustments that are convenient may aid a great deal in making the system workable. Figure 39 is a close-up of the beam-splitter mount coupled with a photodiode housing. It is adjustable for height of the beam-splitting plate and will accommodate plate thicknesses up to 1/4 inch in V-shaped channels. Both the plate mount and the detector can be rotated with respect to the beam. In addition, the plate can be tipped by a fine-thread screw. Springs take up the play in this apparatus.

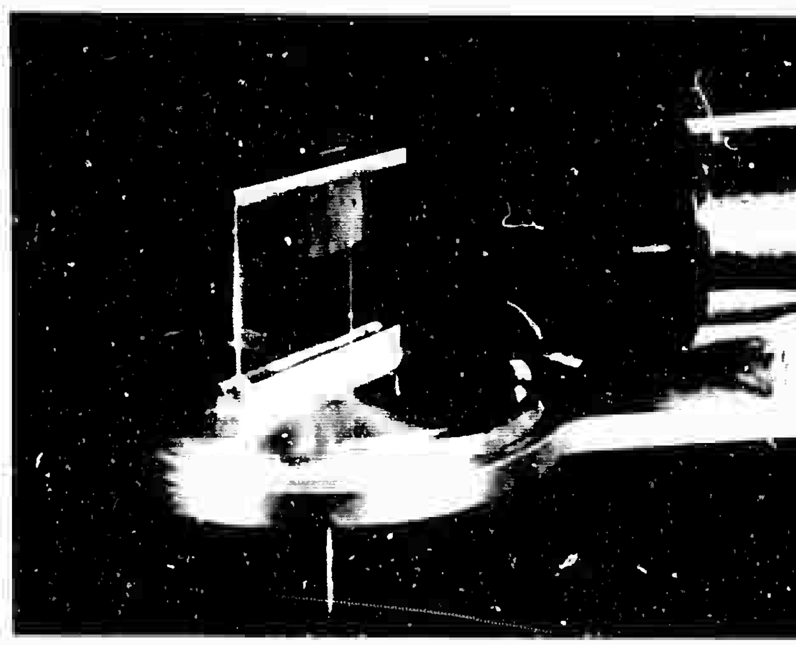


Figure 39. Beam Splitter Detail

Typical applications of the techniques previously described are shown in the following illustrations. In figure 40, the beam splitter on the right feeds its beam into a noisless screen room where a detector is placed. The device on the left in the picture is a foil-bolometer integrator. In figure 41, a Korad laser[19] is on the right, a Korad-housed IT&T FW114 photodiode is in center rear, and a beam splitter mounted left. The diode is used here either for integration or for time resolution of the signal

[19] Korad Corporation, Santa Monica, Calif

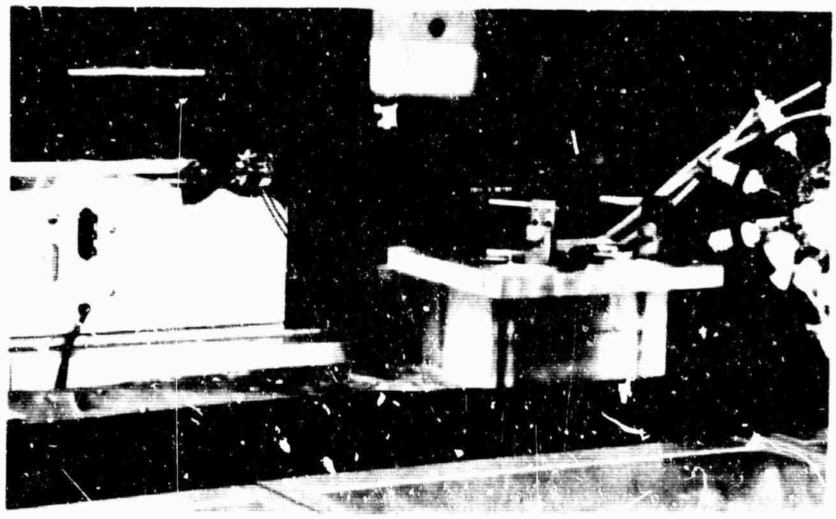


Figure 40. Sample Output Beam-Splitter System

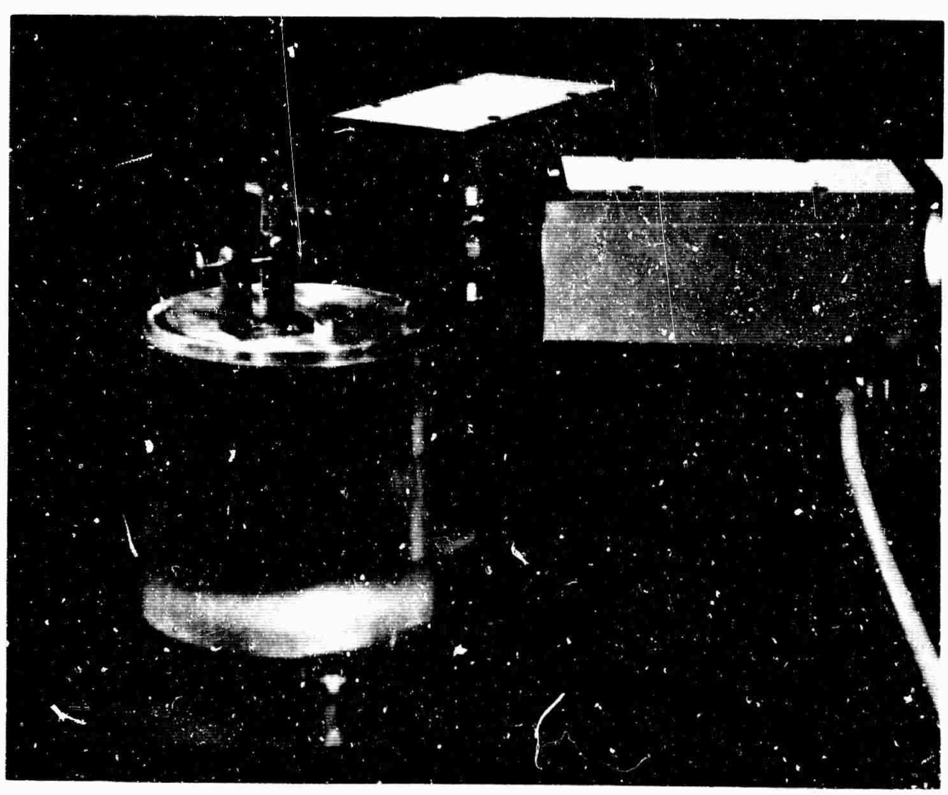


Figure 41. Korad Laser and Photodiode Mounts

The optical train of most laser systems is mounted on an optical bench similar to that shown in figure 42. The train consists of several heads, Q-switching apparatus, and input instrumentation. This train must be quite rugged because the discharge of current through the flashlamps produces forces which act on the heads and can alter the alignment. For larger systems with larger energy discharges, the need for ruggedness and rigidity increases still further. In this setup, 20,000 joules of electrical energy are discharged through each head.

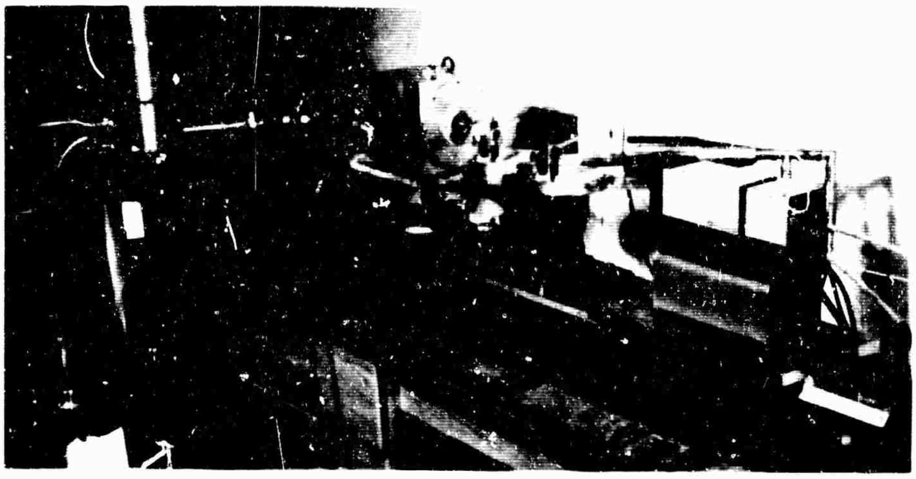


Figure 42. Laser Optical Train

Figure 43 illustrates the massive steel and concrete base required for the oscillator/amplifier train.

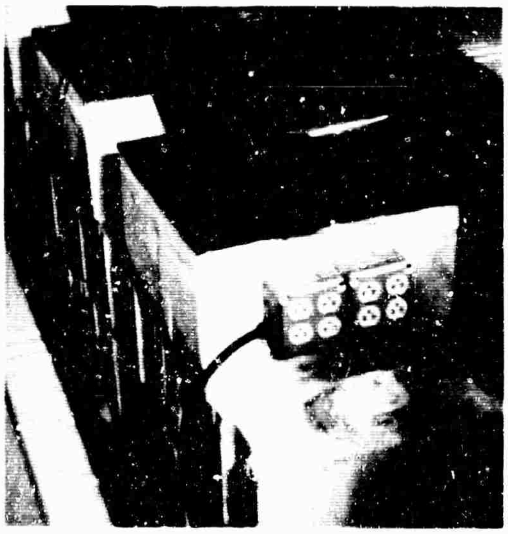


Figure 43. Base for Oscillator/Amplifier Train

2. Electrical Problems

Sometimes it pays to isolate the time-resolved detector ground from the high-energy discharge ground. High currents course through the ground circuit, resulting in relative potentials which can cause signal distortion. Flashlamp triggers can also cause electrical noise, though the housing and shielded cables help keep that under control. Noise caused by nearby high currents may be a problem, since common shielding does not substantially protect against magnetic fields. Distance solves both problems but complicates the alignment. However, if the optical train is sufficiently rigid, such an approach might be worthwhile for other reasons as well, e.g., the vulnerability of the components to interference and the convenience of short electrical cables.

The housing and associated apparatus for IT&T's F114, which was described previously, has a ground shell which completely surrounds the interior components of the tube (completed by the anode screen) and circuitry. Another housing recently made commercially available (but which does not provide for filters or mounting) also shields the tube entirely.[20] It is shown in figure 44.

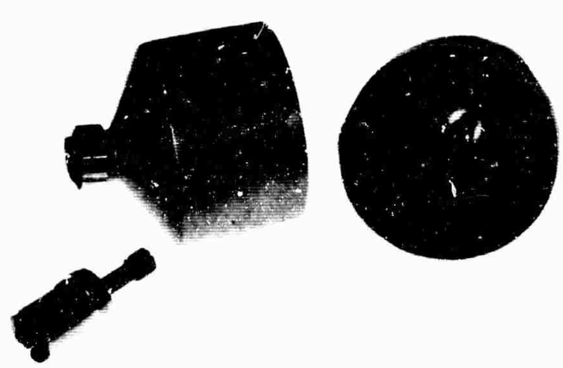


Figure 44. Housing for Photodiode

There are several oscilloscopes capable of 5-nanosecond or better resolution, but signal cables must be terminated in the proper low impedance to utilize such devices. If troublesome reflections do occur, they can often

[20] By IT&T

be isolated through delay cables (about 1-nanosecond delay per foot).

Optically, a bandpass filter is usually needed to cut pumplight interference and, preceding this, for 10^2 to 10^4 attenuation of the incoming beam in addition to the interface reflection of the splitter which feeds about 8 percent of the total beam to the detector system as additional attenuation (and protection).

Beam-splitter plates[21] and attenuating filters[22] are purchased for the Weapons Laboratory high-power lasers in quantity and are merely replaced when they become pitted. As long as lasing crystals can be constructed to withstand the beam, solid-plate beam splitters that will withstand it will be available.

It may also be desirable to filter out pumplight in the integrated signal. The foil bolometer and its filter rack with 6943 angstrom bandpass filter and 0.5 neutral density filter are shown installed in an enclosed chassis box (figure 45). Readout for the foil bolometer is a dc carrier amplifier[23] followed by a pen recorder.

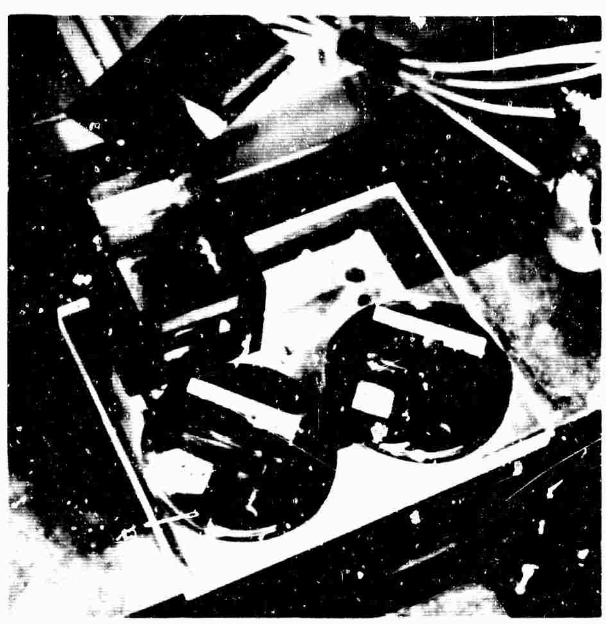


Figure 45. Beam Splitters and Bolometer on Mount

[21] Fused-quartz plates 2 in. x 2 in. x 1/16 in. General Electric type 101, GE Quartz Plant, Cleveland, Ohio.

[22] Kodak neutral density filters are sufficient and relatively inexpensive.

[23] See footnote 3.

3. Accuracy

Greater complexity of the absolute or calibrating system can be tolerated for its relatively brief use. The degree of complexity usually depends on the required accuracy. The results of using such a system depend on the care with which it is used and the quality of the components.

Many applications require accuracies of the order of 3 percent. Extensive precautions which would improve this to 1 percent or better would be essentially wasted. A system which satisfies this need will now be described. The important simplification concerns the use of the same electronics and recorder for the calibration of the sensor as the electronics used in the final laser calibration system. The deflection of the recorder scale is then directly related to the temperature standard. Several intermediate steps are eliminated if this is done and the overall accuracy is improved. The extrapolation error does not appear in this calibration and must be accounted for. Typically, this error will be about 1 percent depending on the equilibrium time and the slope of the decay curve. To this must be added the inaccuracy of the temperature standard and its comparison with the sensor. The slope of this relationship can be expected to be within 1 percent (for two degree changes).

Finally, the stability of the calibrated system in time must be adequate although the calibration (standard-to-sensor) must be checked from time to time. Continuous testing of this type of system over a period of several weeks showed that the equipment described in earlier footnotes can be expected to hold the calibration well within 2 percent. The reproducibility can be noted in two curves in figure 46.

Liquid-filled cone calorimeters and sphere calorimeters have been used in the same system and they agree within the calibration accuracy.

If the corrections for interface reflection of the entering beam are carefully made to the liquid-filled cone calorimeter measurements, the previous estimated accuracies might be applied in this case. The correction would be simpler since the plates do not focus the beam and no vacuum is needed. The principal question might be: Is the beam energy converted to heat rather than being partially involved in some other (stable) internal

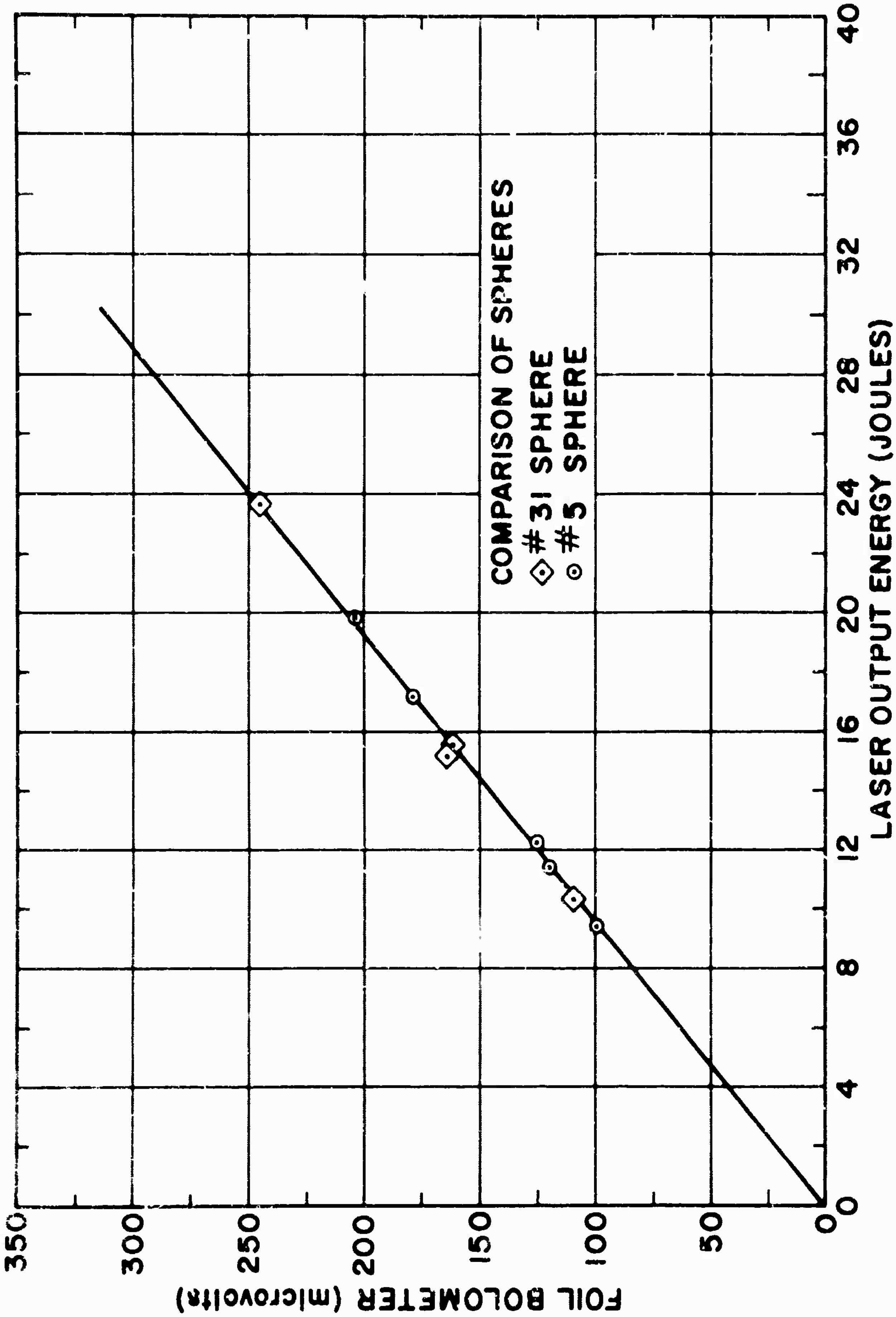


Figure 46. Double Calibration of Foil Bolometers

energy process? A $CuSO_4$ solution is quite satisfactory; many organic substances (and others) are not.

The foil bolometers are as nearly reproducible as anything with which they have been compared. Furthermore, they show no sign of damage after hundreds of shots so that there is no doubt as to their value.

4. Readout System

A few of the readout system details and alternatives will now be discussed. Thermistors require the most readout complexity. It is worth noting that every piece of electronic gear used has failed, partially, at least once during the Weapons Laboratory project, and sometimes deceptively. The calibration or normalization on each shot minimizes these problems plus those of amplifier and component-value drift. Normalization-calibration can also be performed when thermocouples are the sensors if a convenient known reference can be found.

A carrier-operated preamplifier-amplifier-pen recorder system for thermistor control is shown in figure 47.[24]

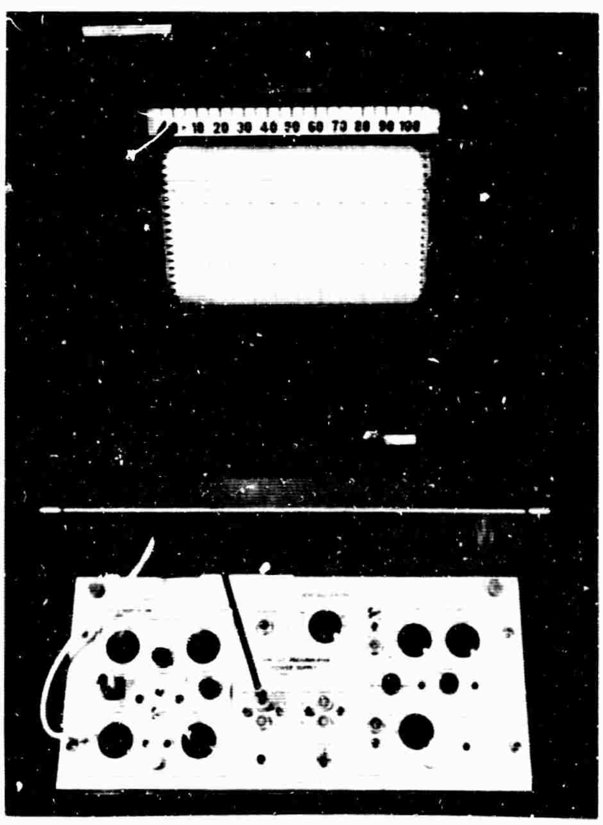
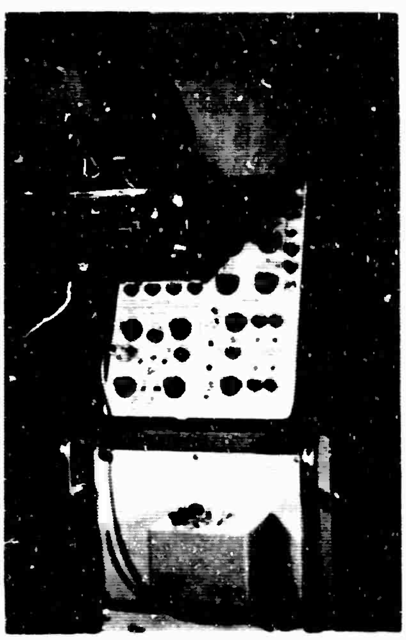


Figure 47. Thermistor Control

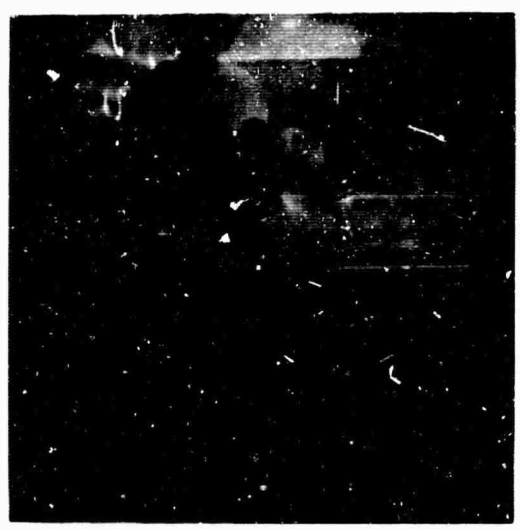
[24] A new unit combining these features compactly is the Sanborn Co., model 7701 recorder and model 8805A preamplifier.

The preamplifier on the right is not used. Preamplifier balance, calibration, power, input, and dummy load controls are located on the horizontal panel. The dummy load consists of three carbon potentiometers in series, which can be substituted in the bridge for the thermistor by an SPDT switch. After the thermistor is balanced, the dummy load is switched in and the potentiometers adjusted to null the signal (balance position on preamp). The base or initial resistance value is then effectively installed in a "memory," to be measured conveniently at a later time. The recorder gives a fairsized permanent record. Another setup which may be more convenient involves using the carrier preamplifier (Tektronix type Q) in an oscilloscope with attached camera. A typical writing rate would be 5 seconds per centimeter. Focusing a dim spot takes practice but clear traces can be obtained this way (see figure 19).

Figure 48 shows the oscilloscope with the thermistor control box mounted and a closeup of the control box.



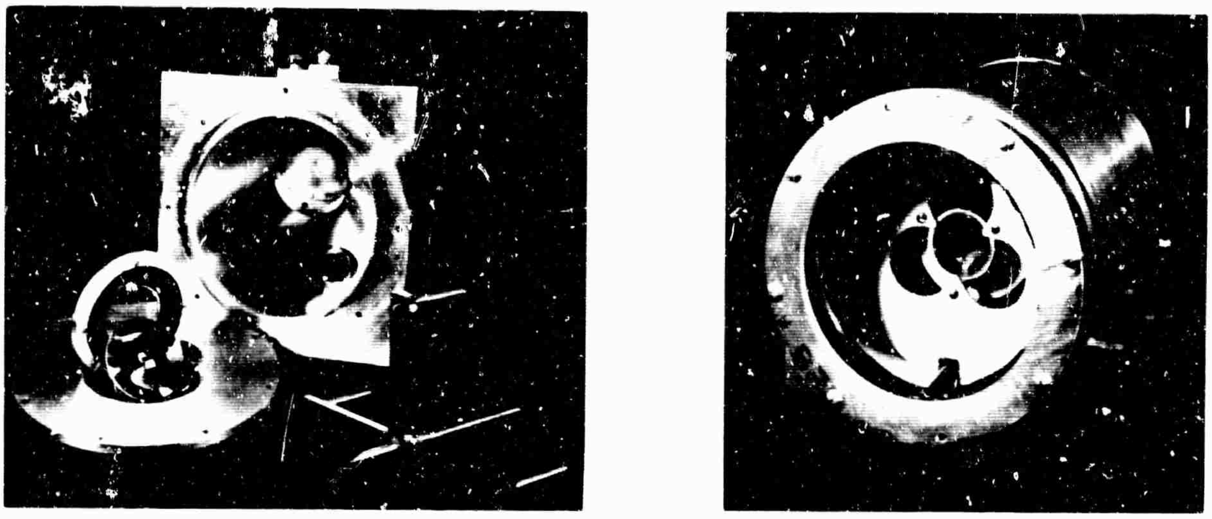
a. Mounted



b. Closeup

Figure 48. Thermistor Controls

Figure 49 details the construction of the sphere and cone calorimeters. The aperture alignment tool, adjustable to various lens focal lengths, is shown on the right in figure 49a.



a. Sphere b. Cone

Figure 49. Sphere and Cone Calorimeter Construction

The calorimeter in its vacuum chamber housing is shown in figure 50. Figure 51 illustrates a calibration resistor and its switching relay mounted on top of the vacuum chamber, a setup used only on the most sensitive calorimeter in this project. It was noted that only with the resistor mounted in this position could correct values be obtained. However, the difference in signal from calibration resistance mounted variously in the line was not relatively large.

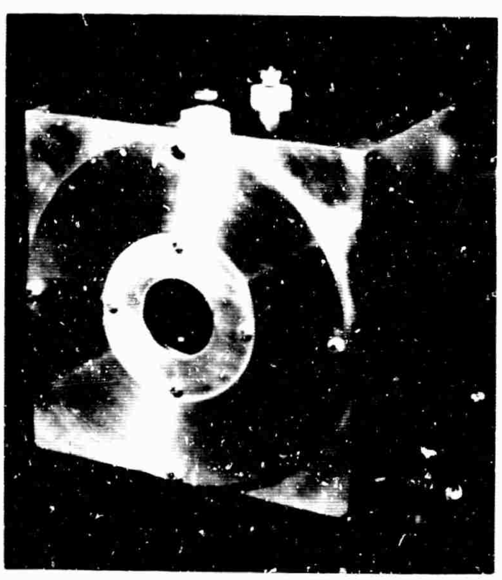


Figure 50. Sphere Housing

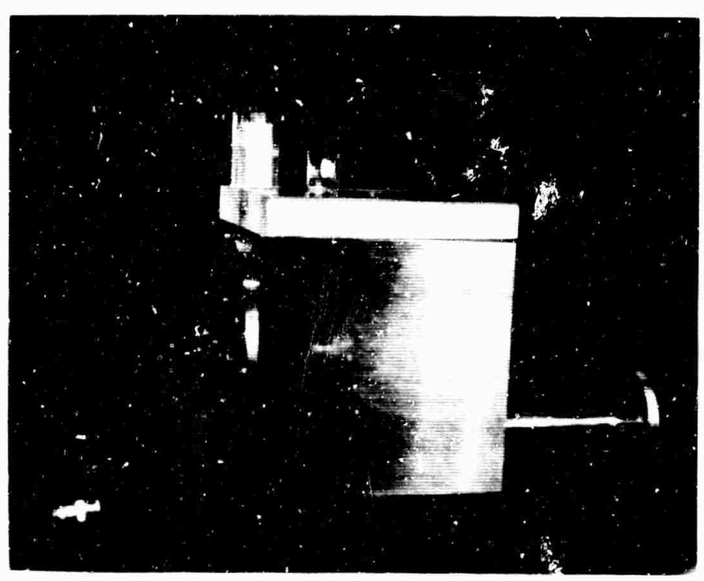


Figure 51. Housing with Resistor

Assorted calibration resistances can be plugged into the banana jacks so that the normalization value will nearly equal that of the thermistor signal for maximum accuracy. The extension and flange connect to the vacuum system.

The thermocouple control unit (figure 52) is quite simple--an amplifier (discussed earlier) and a recorder whose input matches the amplifier output on any scale.

Figure 52. Thermocouple Control Unit

Figure 53 shows the apparatus train to ensure uniformity of response in the IT&T FW114-A phototubes.

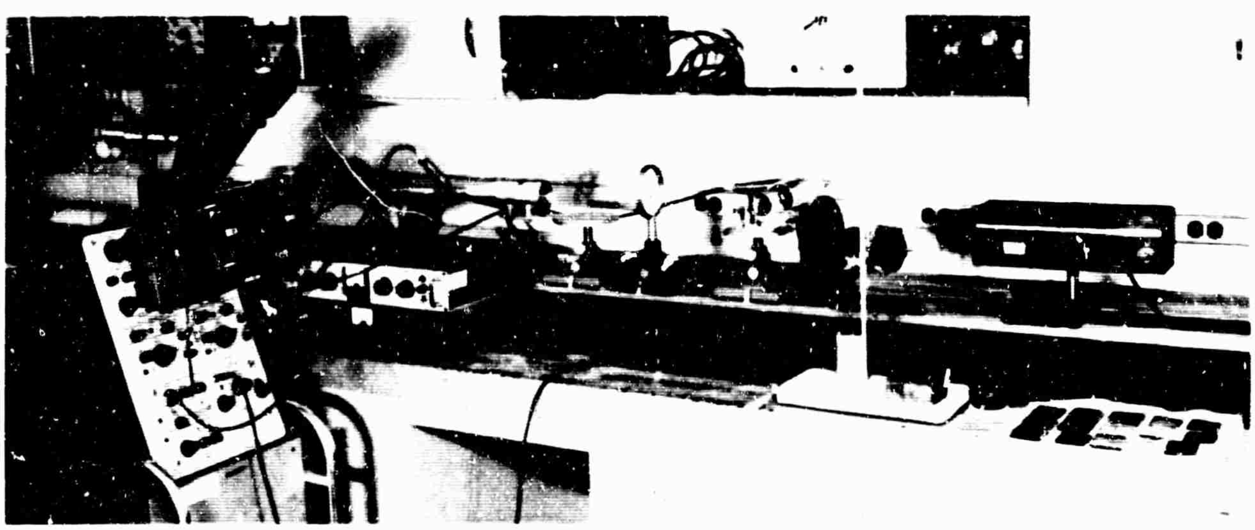


Figure 53. Uniformity-of-Response Apparatus

APPENDIX

PERFORMANCE OF IT&T FW114-A PHOTOTUBES

It is apparent that biplanar phototubes of the type manufactured by IT&T are very well designed for monitoring laser output. However, the purpose of this appendix is to indicate the limitations of these tubes since they do have shortcomings primarily connected with the properties of the photocathode. The weaknesses can be somewhat avoided in the manner as described in the main text of this report. Hopefully, the cathode-coating and chemical stability problems of these phototubes can soon be overcome, thereby greatly increasing their versatility.

Tests were performed on three IT&T FW114-A tubes. These have an S-20 quantum efficiency versus wavelength characteristic. This varies somewhat from tube to tube but the 7,000-angstrom response is relatively good. The test setup used a gas laser source (6,328 angstroms), a mechanical light chopper, a reference or normalizing FW114-A over whose face the beam was defocused, the tube under test with a grid pattern on its face, a double-beam oscilloscope, various power supplies, etc. (Figure 53.)

At no time during the tests was the relationship between the reference tube and the gas laser changed, nor were they even touched. Rather, the tube under test was positioned in the beam by use of an adjustable optical bench mount.

the light-chopping disc was plastic, opaque except for a transparent strip 1/2-inch wide along a radius. This also was positioned in the beam (with an interception radius of 4 inches) and thereafter not moved. The revolution rate was 60 rps, and thus the pulse created was of about 0.35-millisecond duration.

Pulse power supplies of the sort described in the test were mated to AFWL tube housings. Photos were made of a ruled drawing, enlarged, and printed on a negative in the desired grid size with open spaces just large enough so that crossing the anode wires with the beam did not significantly alter the signal determined the grid size. A spectrophotometer check of the grid negative shows that its optical density (between lines) varies by less than 2 percent.

The first test involved determination of the response region which is linear with intensity. The concern was with the state of charge of the capacitor rather than with tube saturation. Neutral density filters were used to set the intensity well within linearity. Application of these tubes to high-power lasers showed saturation to be well above the gas laser level.

The next test was designed to show how the sensitivity of the tubes might vary with time. For 6 hours of tube operation nothing in the optical train was disturbed. It was observed that the normalized signal varies somewhat, but not very rapidly, over a period of minutes. Results are given in table I.

Experiments of this type were performed in 1962 using a Kerr Cell shutter with 10 ns and 50 ns pulse-forming networks, between the light source and a tube (FW114). Pulse shapes over several shots were compared as shown in figure 54, traces from a 50 ns pulse-forming network, measured with the instrumentation setup shown in figure 55.

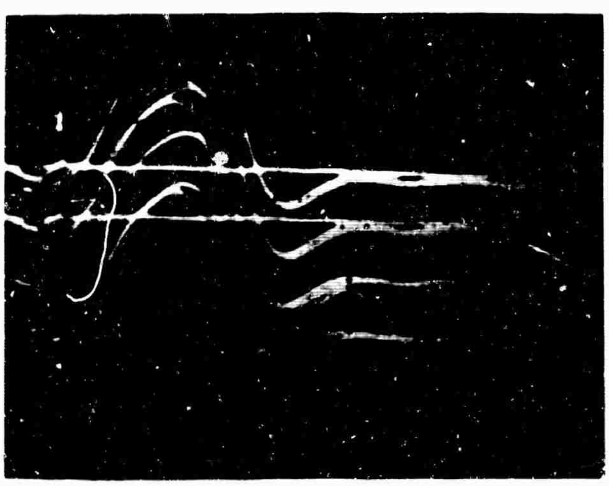


Figure 54. Diode Response to Kerr Cell Shutter

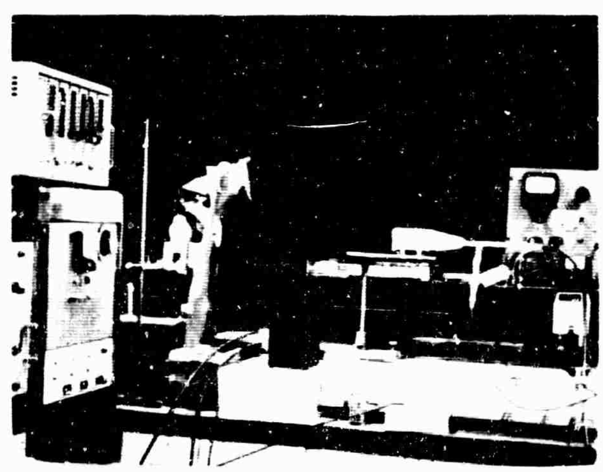


Figure 55. Instrumentation for Diode Response

Table I shows an average deviation from the mean of about ±4 percent and a maximum swing of about ±8 percent.[25]

[25] Both tubes contribute to these variations.

Table I

UNIFORMITY OF RESPONSE WITH TIME

Time in minutes	Normalized signal	Time in minutes	Normalized signal	Time in minutes	Normalized signal
0	0.95	30	0.93	260	1.04
5	0.96	35	0.94	265	1.02
10	1.04	40	0.94	270	1.04
15	0.95	60	1.00	300	1.06
20	1.00	180	1.02	305	1.06
25	0.94	240	1.06		

The tube surfaces were then mapped. This was done rapidly after some practice and was then checked for repeatability, which was found to be within 3 percent (average) for both tubes. The third tube had been tested at least a year earlier under less carefully controlled conditions and thus it is not reported here (the same general observations were made, however).

Surface sensitivity for each tube is mapped in figures 56 and 57. The variation in sensitivity is high although one tube is better than the other in this respect. This suggests that tubes might be selected for uniformity of response until the technology improves.

The important related fact is that pulse ruby lasers do not generally give the same sort of intensity pattern shot after shot; i.e., the brightest spots shift in position. In normal (not Q-switched) operation, the pattern often fills in quite evenly. The result is that, when used with Q-switched lasers, these tubes do not give reproducible, relative-to-intensity pulse heights. In normal operation at the Weapons Laboratory, these tubes have been found to give quite reproducible results. A typical curve is shown in figure 58. A Raytheon elliptical head with FX-47 flashlamp was used. Curves from Q-switched operation have occasional wide swinging points as far out as 40 percent using phototubes plus integrators. The whole surface was not used in these cases, but, even though more area used means better averaging,

	1	2	3	4	5	6
A			1.08	1.12		
B		0.67	0.95	1.12	1.08	
C	0.51	0.69	0.87	1.08	1.39	1.34
D	0.57	0.67	1.01	1.36	1.23	1.11
E		0.71	1.10	1.27	1.18	
F			0.97	1.12		

Figure 56. Response of Diode No. 1

	1	2	3	4	5	6
A			1.10	1.02		
B		1.22	1.02	1.14	0.98	
C	1.08	1.06	1.02	0.96	0.90	0.88
D	0.95	0.98	1.07	0.94	0.98	0.87
E		1.06	1.06	0.93	0.97	
F			0.92	0.97		

Figure 57. Response of Diode No. 2

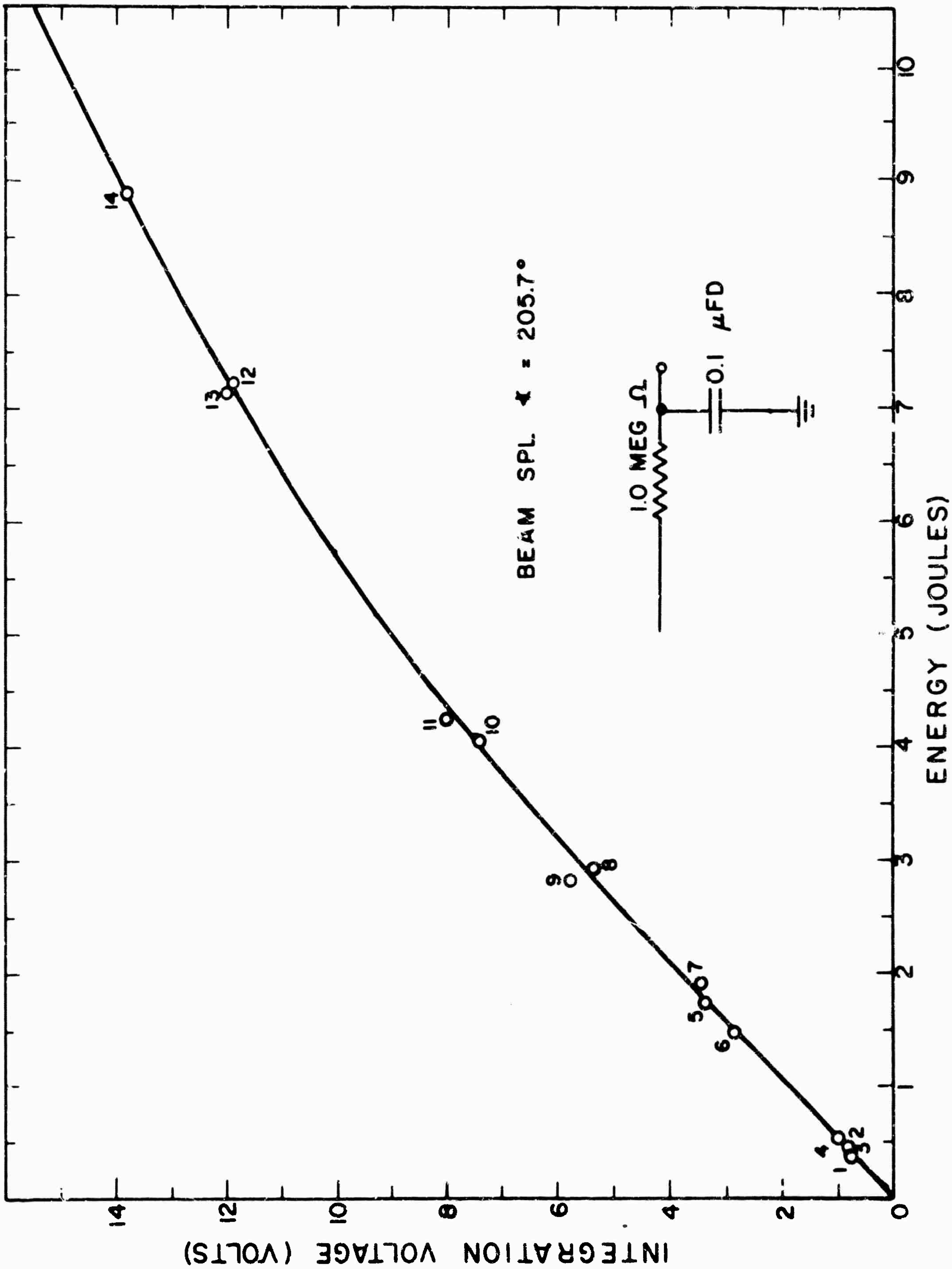


Figure 58. Raytheon Output Calibration

the "mobile hot spots" generally present in a high-power beam force users to look elsewhere for a relative integration. Usually, though, a determination of the power using the phototube signal for pulse shape is acceptable, since in single-pulse lasing a number of independently varying modes do not fall on different parts of the photocathode (in a single shot) and, in the long pulse, the power is often an average over time.